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A NEW FACILITY DESIGN AND WORK METHOD

FOR THE QUANTITATIVE FIT TESTING LABORATORY

A
THESIS

Presented to the Faculty of the Graduate School of

St. Mary's University in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCES

IN

INDUSTRIAL ENGINEERING

BY

G. Frederic Ward, B.S.

San Antonio, Texas

May, 1989

D

A NEW FACILITY DESIGN AND WORK METHOD FOR THE QUANTITATIVE FIT TESTING LABORATORY

G. Frederic Ward

St. Mary's University, 1988

Supervising Professor: Antonio J. Dieck, Ph.D.

The United States Air Force School of Aerospace Medicine (USAFSAM) tests the quantitative fit of masks which are worn by military personnel during nuclear, biological, and chemical warfare. Subjects are placed in a Dynatech-Frontier Fit Testing Chamber, salt air is fed into the chamber, and samples of air are drawn from the mask and the chamber. The ratio of salt air outside the mask to salt air inside the mask is called the quantitative fit factor. A motion-time study was conducted to evaluate the efficiency of the layout and work method presently used in the laboratory. A link analysis was done to determine equipment priorities, and the link data and design guidelines were used to develop three proposed laboratory designs. The proposals were evaluated by projecting the time and motion efficiency, and the energy expended working in each design. Also evaluated were the lengths of the equipment links for each proposal, and each proposal's adherence to design guidelines. A mock-up was built of the best design proposal, and a second motion-time study was run. Results

over

from the two motion-time studies were compared, and showed that the new laboratory design and work method improved time and motion efficiency, and reduced energy expenditure. When implemented, the new laboratory design and work method are expected to save more than $6,000.00 over the next five years. Worker output was also improved. Results showed that with the new laboratory and work procedures, the USAFSAM analyst could test 116 more subjects per year than are currently tested. Finally, the results of a questionnaire given to the analyst indicated that user acceptance of the work area improved with the new design.

Keywords; test method; Fit testing; (KT)

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PREFACE

This thesis involves the facilities design for the Quantitative Fit Testing Laboratory at the United States Air Force School of Aerospace Medicine at Brooks Air Force Base, San Antonio, Texas. The laboratory is used to test the quantitative fit for masks worn by military personnel during nuclear, biological, and chemical warfare. The laboratory layout and work procedures were evaluated, and inefficiencies were found. A more efficient design and work method was developed and implemented. It was hoped that this thesis would provide a design and work method which would make the quantitative fit testing process more efficient.

Preliminary research began in March 1988, data collection started in July 1988, the thesis went to committee on 25 October, and the committee met and gave final approval on 4 November 1988.

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A very special thank you to Dr. Turgut Ozan, who provided guidance with his laboratory performance improvement model and with motion-time study procedures; Dr. Willie Silva who provided his design expertise; Mr. Alex Slate who provided guidance, support, and timely feedback throughout the project; and Dr. Antonio Dieck, supervising professor. Finally, this thesis would have never been possible without the constant support provided by my wife Stephanie. Thanks Steph!

TABLE OF CONTENTS

CHAPTER NUMBER PAGE

CHAPTER NUMBER | PAGE

LIST OF FIGURES

LIST OF TABLES

Chapter 1

INTRODUCTION

1.1 BACKGROUND

As world tensions continue to grow, the need to acquire and develop new defense technology increases. The spectrum of technology already available is broad, ranging from simple hand held weapons and stealth bombers to nuclear, biological, and chemical (NBC) contaminants.

The United States currently conducts research which is intended to help our military personnel during an NBC war. Masks worn by military troops are tested for leakage at the United States Air Force School of Aerospace Medicine (USAFSAM). A new laboratory was designed for the purpose of testing the quantitative fit of masks used in NBC warfare.

1.2 PURPOSE

The objective of this project was to provide USAFSAM with a work method and laboratory design which would enable the analyst to perform laboratory tasks in the shortest possible time and with the greatest ease and satisfaction. The analyst's job was designed so that it resulted in the lowest possible energy expenditure. Through an extensive analysis, which included interviews, a questionnaire, motion-time (MT) studies, link analysis, energy expenditure, and design guidelines, an improved laboratory facility and work method were developed.

1.3 OVERVIEW OF THE THESIS

In this project, the analyst in the Quantitative Fit Testing Laboratory was video taped as he setup the laboratory and tested a subject wearing a MBU-13P mask. The activities performed (motions) by the analyst were noted and defined. Later, each of the defined motions were timed in order to determine which activities consumed most of the analyst's time. Using this information, the analyst's activities were changed to reduce the setup and testing time. This involved redesigning the laboratory. Interviews were conducted and a questionnaire was administered to determine the good and bad points of the current and the proposed design. A link analysis was performed on the analyst's movements from one piece of equipment to another to establish the frequency with which the components were linked and the importance of the links. Controls on the consoles, and the computer were then relocated according to their priority to the analyst and to design guidelines. The amount of energy spent by the analyst working with the old and the new designs was approximated using available data and compared.

In Chapter 2, the Quantitative Fit Testing Laboratory, the procedures used in the laboratory, and the current design problems are described. Chapter 3 is a literature review of the system design process, motion-time studies, link analysis, energy expenditure data, and design

guidelines. Chapter 4 is the methodology section which includes subjects, apparatus, and evaluation procedures used in the motion-time studies, methods analysis, and link analysis. Also described are the procedures used to compare energy expenditure data and the design guidelines, as well as cost reduction and questionnaire procedures. Chapter 5 describes three laboratory design proposals. Chapter 6 is a description and comparison of the results, and Chapter 7 presents a summary and recommendations.

Chapter 2

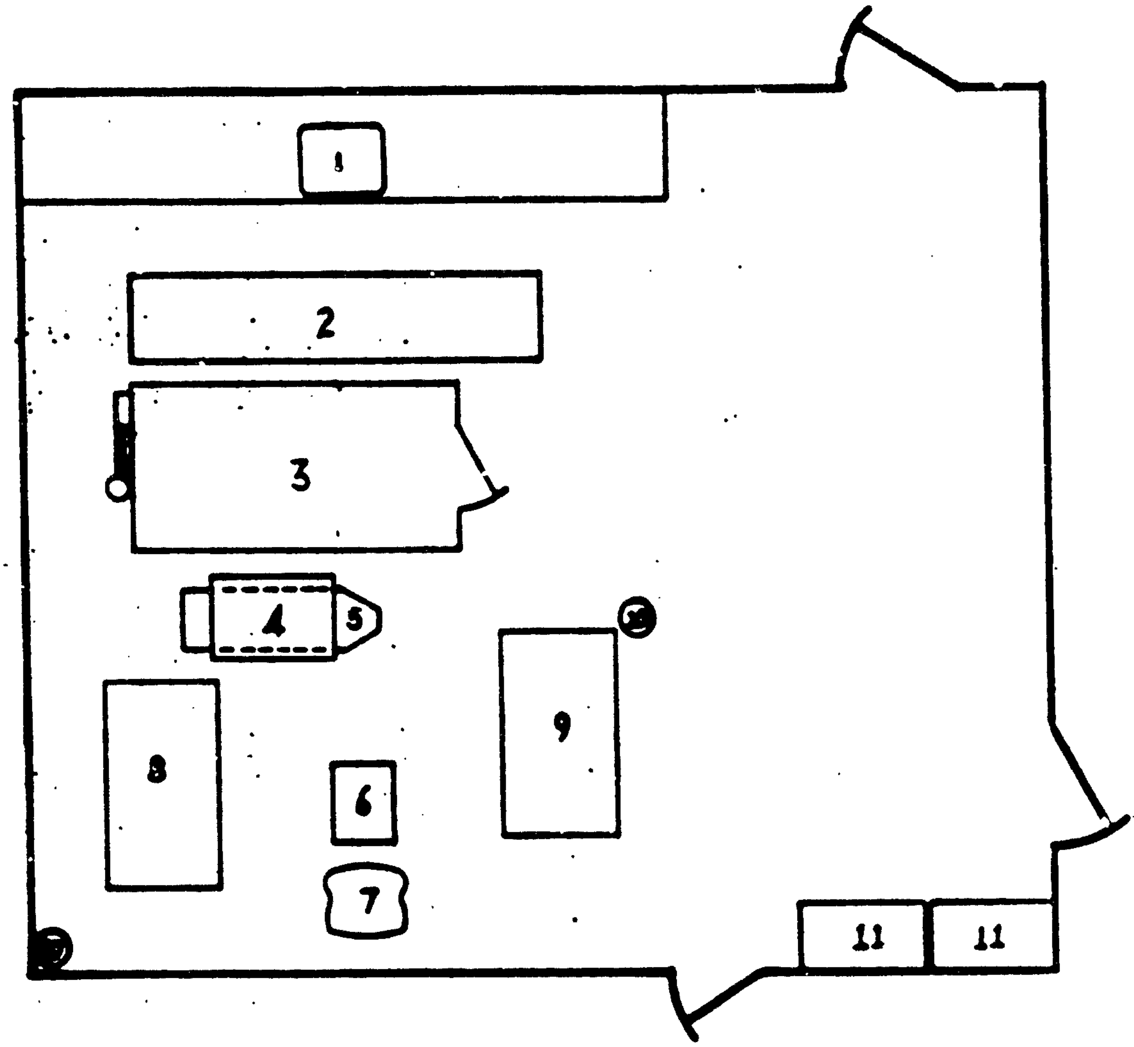
DESCRIPTION OF THE QUANTITATIVE FIT TESTING LABORATORY

2.1 BACKGROUND

The Quantitative Fit Testing Laboratory at the USAFSAM (Brooks Air Force Base, Texas) tests for leakage in the three main types of masks worn by United States Air Force personnel. These masks are the M-17 series, which are ground crew masks (being phased out), the MBU-13P (pilot's mask), and the MCU-2/P which is the new ground crew mask, replacing the M-17 series. Subjects are placed in a testing booth wearing one of the three masks, and a vaporized salt solution is fed into the booth. Over time, samples of air are drawn from the mask to determine the amount of contamination (salt solution) that has leaked into the mask. Results are then compared with standard data and generalized to nuclear, biological, and chemical warfare.

2.2 CURRENT LABORATORY LAYOUT

Figure 2.1 depicts the current laboratory layout. During set up, the analyst spends most of his time at the sink making saline solution or at the consoles calibrating instruments. The three calibration, or air flow, instruments are the calibration drying air, sample carrier air, and the atomizer air. Travel between the sink and the two consoles is frequent, but access to the consoles is unnecessarily long and difficult due to protruding pipes,



1: Sink
2: Extra Equipment
3: Fit Testing Booth
4a: Integrator Box and Data Logger
4b: Integrator Box and Disk Drive
5: Air Source
6: Computer
7: Chair
8: Booth Panel
9. Mask Panel
10: Hydrogen
11: Storage Cabinets
12: Printer Stand
13: DC Power Source

Figure 2.1 The Current Laboratory Layout

electrical wires, and insufficient walk space. For safety reasons, the sink cannot be located with the consoles, however, the consoles could be brought closer to the sink to reduce the walking distance. The consoles are shown in Figure 2.2 and 2.3. While calibrating the instruments, line-of-sight to the integrator boxes is necessary. Although line-of-sight is currently not a problem, the analyst has the option of taking readings from the integrator boxes (See Figure 2.4) from six feet away or walking closer to get a better view.

During testing, the focal point of the analyst's activities is the computer. The computer equipment is shown in Figure 2.5. The analyst frequently walks between the computer and the consoles. To do this, he must place the keyboard on top of the computer and carry the intercom as he walks to the booth console. Restricted by the length of the intercom cord, the analyst must then put the intercom back before walking to the mask console. After inspecting and adjusting the air flows to the mask, the analyst returns to the computer and sits down.

The literature indicates that chairs and seating posture are presently receiving a lot of attention because of worker absences due to neck and back problems. Nussbaum [1985] stated that a properly designed chair can add as many as 40 productive minutes per day for most office workers, which is 21 productive days per year. Problems occur most

Figure 2.2 The Current Mask Console

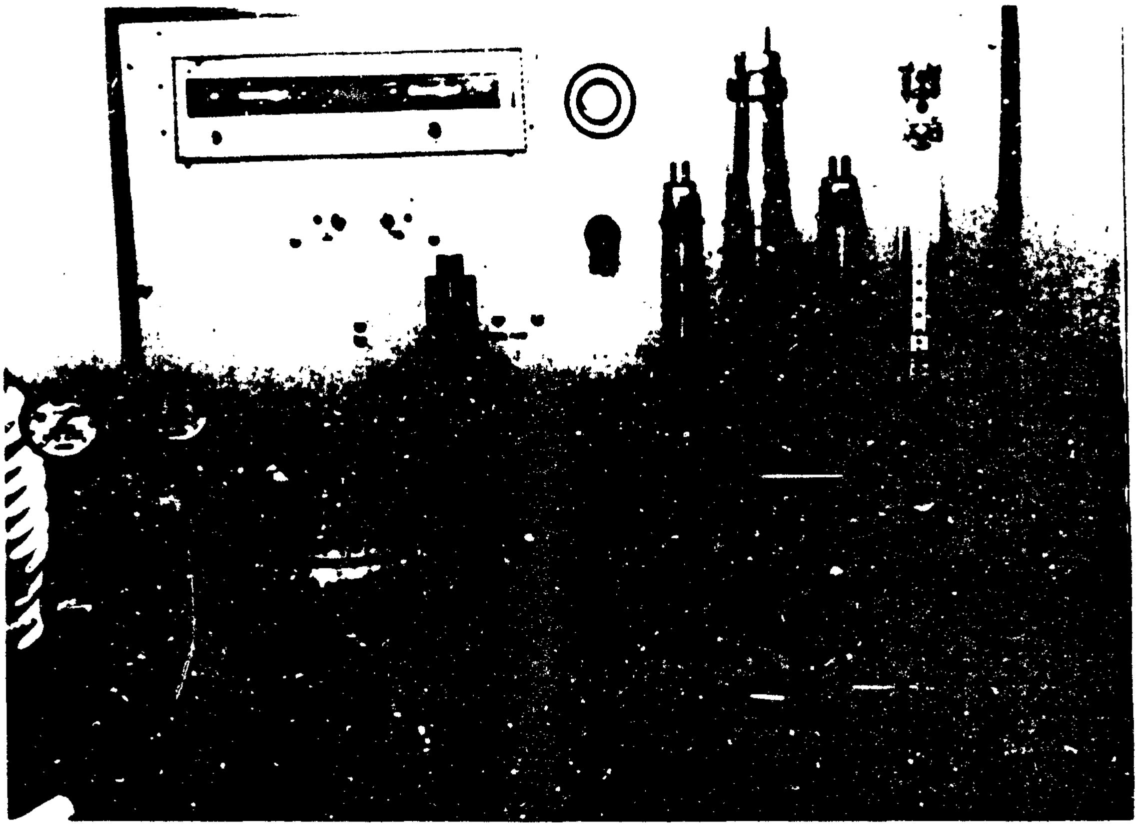


Figure 2.3 The Current Booth Console

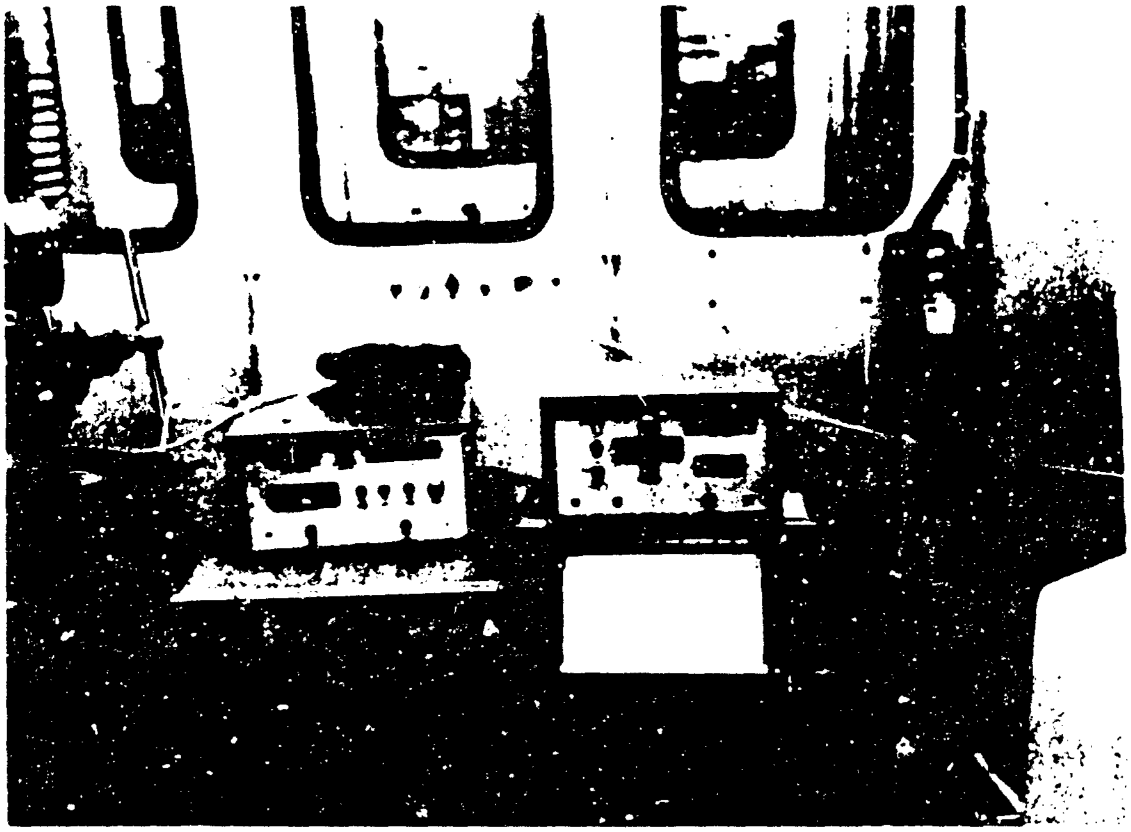


Figure 2.4 The Current Location of the Integrator Boxes
(Integrator Boxes are the Top Two Boxes)

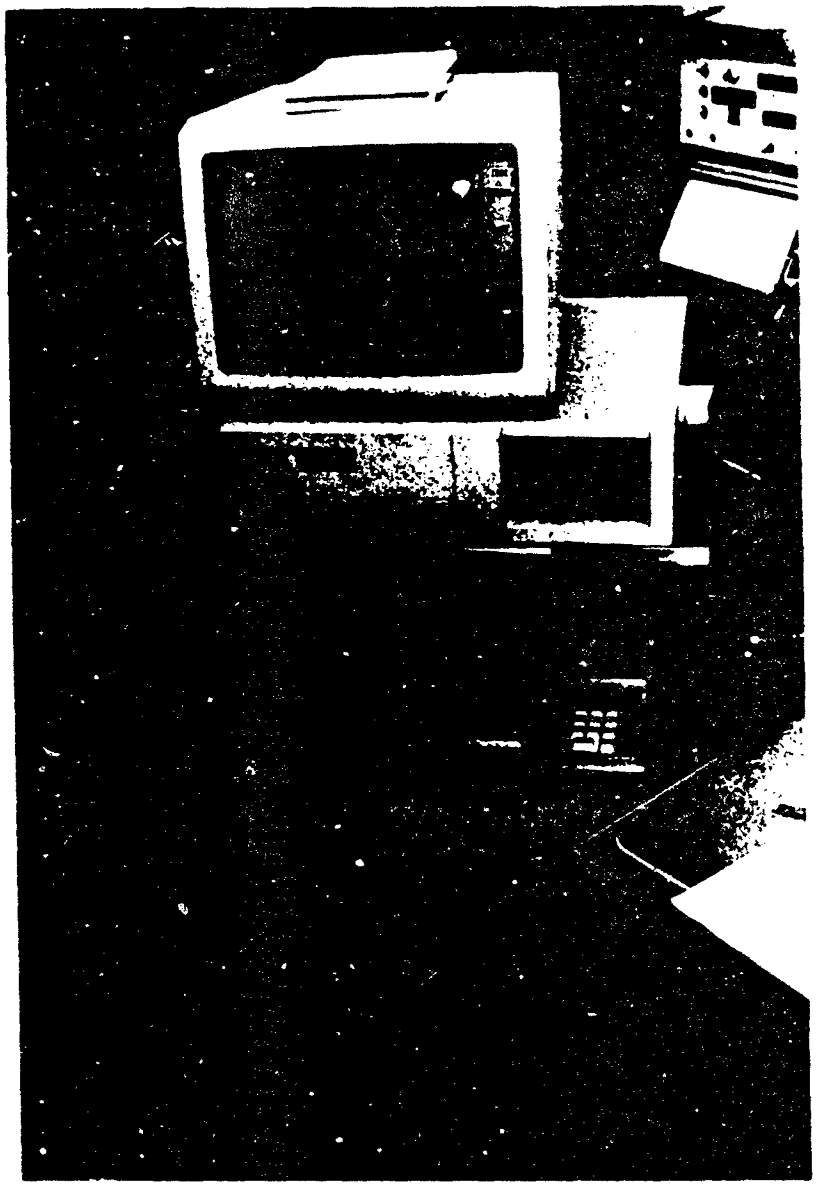


Figure 2.5 The Current Setup for the Computer Equipment

often for workers in sedentary jobs such as data entry. The chair used in the Quantitative Fit Testing Laboratory is similar to chairs found in living rooms of homes. The seat cushion is stuffed as are the arm rests and back support, making it a very comfortable chair to sit in. The chair's utility was limited, however, because it could not be adjusted to different heights. In fact, the analyst had to hold his head back at an angle of 20 degrees above horizontal, in order to see the computer screen. The analyst's comfort was a concern in this study, as were time and motion efficiency and energy expenditure.

From the time study, setup time, testing time, and total time were determined for the fit testing process. A functional flow diagram (Appendix A) of the process was constructed and was used to conduct a methods analysis. From the methods analysis, the distance traveled by the analyst during setup and testing was determined, as was the amount of energy spent. The present study sought to determine if the time required, the distance traveled, and the energy expended could be reduced.

2.3 SYSTEM PERFORMANCE OBJECTIVES AND CONSTRAINTS

System performance specifications include ensuring the proper mix of salt and air which enters the booth, drawing samples of air from the subject's mask, communicating with the subject via an intercom system, and providing input to the computer about the subject and the type of mask used.

System constraints includes the floor space available in the new laboratory. An area 20 feet four inches by 26 feet four inches was allocated for the laboratory. The air flow line, which ran from the vertical flame to the pump, and then to the booth had to be as short as possible. This constraint was addressed throughout the project. Money was not available to purchase new equipment because the project began late in the fiscal year. Water faucets, electrical power sources, and air connections were needed. Water is necessary to make salt water, electrical outlets are the source of power for the system, and air connections are used to flush the tubes which carry salt air to the booth and from the mask. Time was also a system constraint. Due to the amount of time required to setup and test in the laboratrry, the number of subjects who could be tested each day was restricted to eight.

2.4 OVERVIEW OF THE LABORATORY DESIGN PROBLEMS

The research conducted in the laboratory is vital to the Air Force. However, the apparatus and methods used were evaluated, and several inefficiencies and hazards were detected. Some of these problems included: 1) tubes carrying the salt solution hung in walkways and were draped across other equipment, creating a safety hazard, 2) the computer, which stores data from the mask and booth, was located on a laboratory cart, 3) the computer keyboard sat on top of the computer terminal requiring the analyst to

stand or place the keyboard in his lap every time he made an entry, 4) some of the motions performed by the analyst were redundant, 5) the printer for the computer sat on the middle shelf of the laboratory cart, and due to a lack of feeding space, computer paper going into the printer interfered with paper being fed from the computer and caused printer problems, 6) due to the location of the printer, retrieving printouts was inconvenient, 7) many of the calibration instruments, the vertical flame, the air compressor, and electrical cords were located in the walkway and could easily be bumped accidentally, 8) the analyst spent most of his time between laboratory tests walking from one piece of equipment to another, and 9) the control consoles for the booth and mask were on opposite sides of the laboratory which meant the analyst had to step over electrical wires and tubes when walking between the two consoles.

2.5 PURPOSE OF THE RESEARCH

The problems described above resulted in a loss of testing time, redundancies in work methods, and unnecessary worker fatigue and dissatisfaction. These problems occurred because of a general disregard for human factors engineering design. The Air Force Systems Command Design Handbook [1980] lists the following six objectives of human factors engineering: improve performance, reduce training costs, improve manpower utilization, reduce losses of time and equipment, increase economy in production and maintenance,

and improve user acceptance. With these human factors objectives in mind, the aim of this project was to redesign the laboratory in such a way that the process of setting up and testing became more efficient and improved user acceptance, while maintaining the accuracy and effectiveness of the testing program.

There are a number of methods available for improving efficiency. The first step is to evaluate the worker's job performance; first through work measurement, and then through work methods. Chase and Aquilano [1985] listed the following ways to evaluate job performance through work measurement: film analysis, stopwatch time study, elemental data, and work sampling. Because the activities in the laboratory were repetitive and had relatively short time intervals, a stopwatch time study and film analysis were used. The techniques for studying work methods include: flow diagrams, process charts, operations charts, simo charts, application of the principles of motion economy, activity charts, worker-machine charts, and gang process charts. In this study, flow diagrams and the principles of motion economy were applied to determine and correct inefficiencies in the analyst's work methods. After the analyst's job was broken down into individual activities, it was possible to measure the amount of strain induced by job-related stress. Two ways of measuring strain are physiological measures and psychological measures.

Physiological measures are shown in Table 2.1. The electrical measures were too laborious to measure all day,

Physical	Chemical	Electrical
Blood pressure	Urine content	Electroencephalogram
Heart rate	Oxygen consumption	Electrocardiogram
Sinus arrhythmia	Oxygen deficit	Electromyograph
Pulse volume	Oxygen recovery curve	Electooculogram
Pulse deficit	Calories	Galvanic Skin response
Respiratory rate	Blood content	
Body temperature		

Table 2.1 Primary measures of strain as induced by stress (Sanders and McCormick [1987]).

as were many of the chemical and physical measures; so for this study, energy expenditure (kcal/min) was used as a measure of stress. The literature contains charts which listed the physiological costs of activities similar to those activities performed in the laboratory.

Psychological measures include: work rate, errors, boredom, absenteeism, and employee turnover (Sanders and McCormick [1987] and Muchinsky [1983]). Like many of the physiological measures, the measurement of work rate was laborious. Boredom was not an appropriate measure for the purposes of this study, and absenteeism, turnover, and errors were not a problem, so none of the psychological measures were used. In addition to MT studies and energy expenditure analysis, design guidelines were followed to ensure that the work console was optimally designed.

Three alternative designs were presented in this study. The one design which was expected to be most efficient was

recommended, and a functional mock-up of that design was built. Analyses, using the mock-up, included measurement of productivity and cost savings. One result of efficient design is improved productivity (masks tested per day) from labor. Any productivity increase realized through better design was discussed. A second result of efficient design is cost savings. Cost has become especially important to the Department of Defense due to budget constraints, so the amount of money saved by implementing the new layout was also determined.

2.6 PROCEDURES USED WHEN TESTING A MASK FOR LEAKAGE

The Quantitative Fit Testing Laboratory tests the "quantitative fit factor" for masks worn by a variety of USAF personnel. Quantitative fit factor is defined as a dimensionless ratio of the contamination level outside the mask to contamination levels inside the mask caused by peripheral seal leakage or manufacturing defect sites (Slate [1988]). Quantitative fit testing is done by civilian industries using dioctal pythalate (DOP) instead of salt-air, used by the military. Dioctal pythalate is carcinogenic and does not provide the sensitivity that salt provides. Greater sensitivity in quantitative fit testing is necessary because military applications include NBC warfare.

When a subject arrives to be tested, he/she is briefed on the testing procedures, dons a mask, and enters the

Dynatech-Frontier Fit Testing Chamber. Salt (NaCl) air is then fed into the booth via a plastic air tube. Samples of air are continuously drawn from the subject's mask by a data logger and are input into a computer. As samples of air are being drawn, the subject is instructed to perform a series of exercises. The exercises include normal breathing, deep breathing, movement of the head from side-to-side, movement of the head up and down, reading of a written passage which is taped to the inside of the booth, and making facial expressions. These exercises are designed to simulate the stresses that a mask would face in a normal environment (Slate [1988]). Once each of the six exercises is completed, the procedure is repeated with the second and third masks.

The process of testing a subject is directed primarily by the computer. The analyst plays two roles. The first is to respond to each computer prompt by issuing a verbal command to the subject. The second is to monitor six calibration instruments (two each of the atomizer air, calibration drying air, and sample carrier air) in order to insure a proper salt air mix.

Once the subject enters the booth, the analyst presses the "enter" key on the keyboard, enters data specific to the subject and mask, and then responds to the prompts which appear on the visual display terminal (VDT). While waiting for each prompt, the analyst must constantly monitor the

amount and concentration of salt air flowing into the booth. This involves adjusting the control for the sample carrier air which dilutes and transports salt air to a flame insuring that the air entering the booth is clean and dried. Adjustment of the calibration drying air may also be necessary. The calibration drying air is used to dry the aqueous solution of salt, thus leaving salt air. A third adjustment involves the calibration atomizer air which creates an aerosol of salt and water. The proper salt air mix for the booth is maintained by controls for the sample carrier air, calibration drying air, and atomizer air. The mask has its own set of controls for these three calibration instruments, therefore, the analyst has a total of six instruments to monitor in addition to making responses to the computer prompt.

At 30 second intervals, the computer prompts the analyst to instruct the subject to perform one of the six exercises. The analyst then presses the intercom button and gives one of the following instructions:

BEGIN NORMAL BREATHING

BEGIN DEEP BREATHING

MOVE YOUR HEAD FROM SIDE-TO-SIDE

MOVE YOUR HEAD UP AND DOWN

READ THE WRITTEN PASSAGE HANGING ON THE WALL

MAKE FACIAL EXPRESSIONS

After an individual subject has been tested with the three masks, another subject can begin. Following testing of a group of subjects, data are gathered and compared to available standard data. The results are then generalized to NBC warfare.

With a clear understanding of what the Quantitative Fit Testing Laboratory does and an understanding of some of the general design problems that exist in the laboratory, the pertinent literature will now be reviewed.

Chapter 3

LITERATURE REVIEW

3.1 SYSTEM DESIGN

A system is the combination of hardware, information, and people necessary to accomplish some specified mission (Dieter [1983]; Bailey [1982]; and Sanders and McCormick [1987]). The human-machine system being designed in this project is classified as a closed-loop, mechanical system. Sanders and McCormick [1987] define a mechanical system as one in which the machine typically provides the power, and the human operator provides the control. A closed-loop system is continuous, meaning that the system requires continuous control and continuous feedback in order to function properly. The basic functions performed by a human in a human-machine system are shown in Figure 3.1.

3.2 SYSTEM DEVELOPMENT

Dieter [1983] lists six steps which comprise the design process. These steps are:

1. Recognition of a need
2. Definition of a problem
3. Gathering of information
4. Conceptualization
5. Evaluation
6. Communication of the design

Most system designers have a list of steps which they use as a guide to proceed through the design process. In Figure 3.2, Blanchard and Fabrycky [1981] describe the process

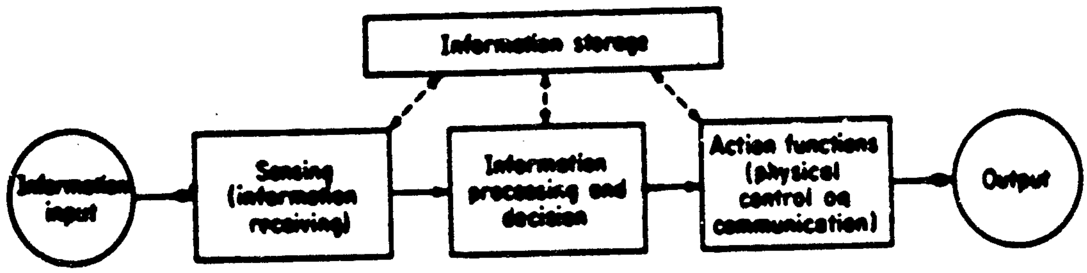


Figure 3.1 Basic Functions Performed by Human and Machine Systems (Sanders and McCormick [1987])

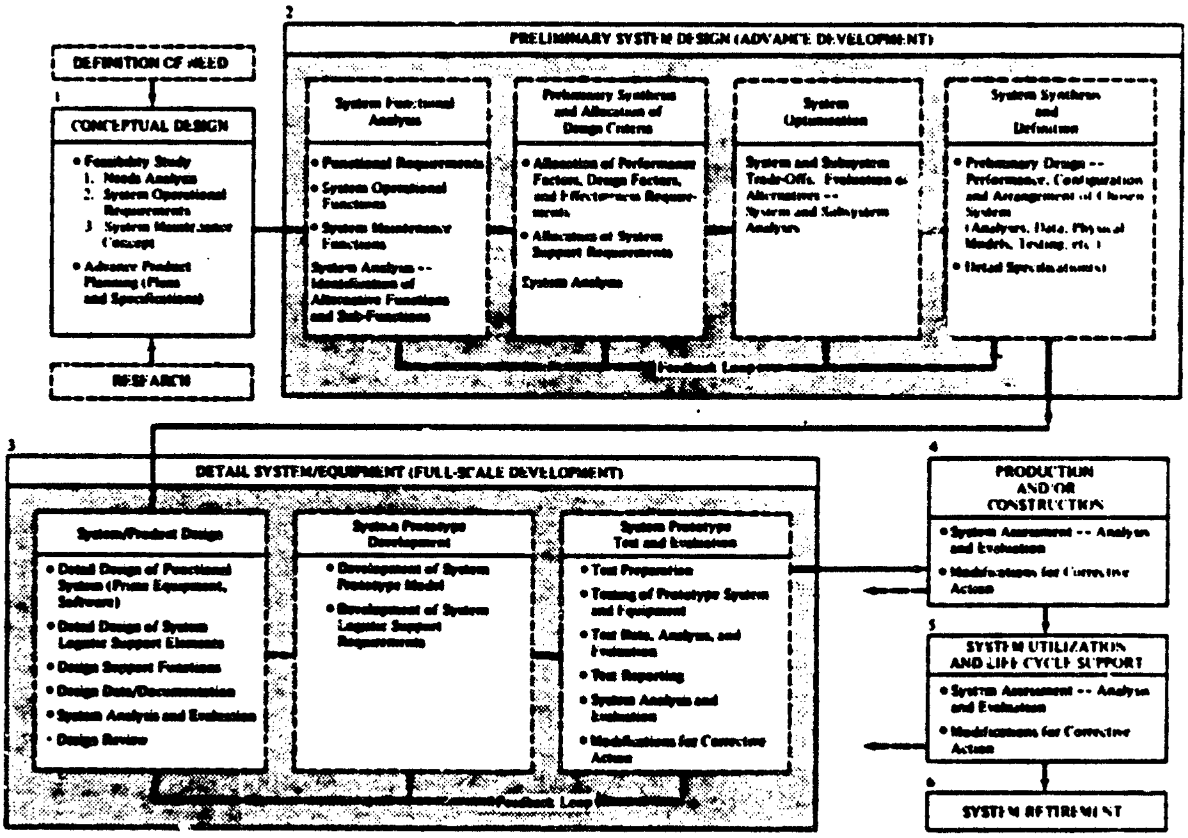


Figure 3.2 System Design Evolution
(Blanchard and Fabrycky [1981])

involved in systems design. This diagram provides a specific breakdown of the stages described by many system designers. Bailey [1982] defined system development stages which included those steps previously listed, and also broke each stage down to a more specific definition. This list is appropriate for use in designing the Quantitative Fit Testing Laboratory. The stages include:

1. Determine objectives and performance specifications
   - A. Determine user needs
   - B. Determine user characteristics
   - C. Determine organizational characteristics
   - D. Determine work flow
   - E. Determine human performance measurement procedures and parameters

2. Define the system
   - A. Determine functional requirements
   - B. Determine performance requirements

3. Basic design
   - A. Allocate functions
   - B. Design work procedures
   - C. Design performance feedback mechanisms

4. Interface design
   - A. Design interfaces
   - B. Design work areas

5. Facilitator design
   - A. Develop staffing requirement
   - B. Design and develop instructions
   - C. Design and develop performance aids
   - D. Design and develop training

6. Evaluation stage
   - A. Develop testing specifications
   - B. Conduct test sessions
   - C. Perform system evaluations

One motion-time (MT) study was conducted which indicated the time and motions needed to perform each task

in the present laboratory. Three laboratory design proposals were then evaluated, and a mock-up of the best proposal was built. A second MT study was conducted using the mock-up, and the results of the two studies were compared.

3.4 MOTION-TIME STUDIES

Two of the pioneers of work measurement were Frederick Taylor and Frank Gilbreth (Lesperance [1953]). Taylor originated the time study for the purpose of determining time standards, while Gilbreth and his wife developed the motion study to improve work methods (Barnes [1968] and McCormick and Ilgen [1985]). The Gilbreths developed the 17 basic motion patterns, shown in Figure 3.3, which were used to describe the motion patterns of almost any job (Christensen [1981]; Niebel [1976] and Barnes [1968]).

Barnes [1968] stated that in the 1930s work studies sought to find better and simpler methods of doing work. Shortly after this, time studies and motion studies were combined. Goals for motion-time studies ranged from determining wage increases based on output to the design of work systems (Fein [1979] and Barnes [1968]).

Around World War II an incentive plan, called the measured day work (MDW), was developed to improve worker and plant productivity (Fein [1979]). Since that time productivity has become a major issue. According to Niebel [1976], the production section of an industry could be

Name of Symbol	Therblig Symbol		Explanation—suggested by	Color	Color Symbol	Dixon Pencil Number	Eagle Pencil Number
Search	Sh		Eye turned as if searching	Black		331	747
Select	St	→	Reaching for object	Gray, light		399	734½
Grasp	G	∩	Hand open for grasping object	Lake red		369	744
Transport empty	TE		Empty hand	Olive green		391	739½
Transport loaded	TL		A hand with something in it	Green		375	738
Hold	H		Magnet holding iron bar	Gold ochre		388	736½
Release load	RL		Dropping content out of hand	Carmine red		370	745
Position	P		Object being placed by hand	Blue		376	741
Pre-position	PP		A nine-pin which is set up in a bowling alley	Sky-blue		394	740½
Inspect	I	0	Magnifying lens	Burnt ochre		398	745½
Assemble	A	#	Several things put together	Violet, heavy		377	742
Disassemble	DA		One part of an assembly removed	Violet, light		377	742
Use	U	U	Word "Use"	Purple		396	742½
Unavoidable delay	UD		Man bumping his nose, unintentionally	Yellow ochre		373	736
Avoidable delay	AD		Man lying down on job voluntarily	Lemon yellow		374	735
Plan	Pn		Man with his fingers at his brow thinking	Brown		378	746
Rest for overcoming fatigue	R		Man seated as if resting	Orange		372	737

Figure 3.3 Fundamental Hand Motions and Their Standard Symbols and Colors Developed by Gilbreth (Barnes [1968])

called the heart of the industry. He also stated that if the production department is considered the heart of the industry, then the methods, time study, and wage payment activity is the heart of the production group. Motion and time studies continue to be popular in industry today, and even though they have been used as work measurement instruments across many industries with differing objectives, they continue to yield useful results.

Wright [1982] a senior consulting officer for a Seattle area bank used MT studies to reduce the time needed to produce and transmit typed materials. MT studies were used first to determine the setup and completion time for a work order. Then, operator time for keystroke inputs and proofreading were determined using stop watches. From the MT data gathered, a production rate table was established which enabled bank supervisors to forecast work load and establish reliable turn around times. Wright [1982] predicted that if properly organized, word processing could improve typing production by, at least, 50 per cent.

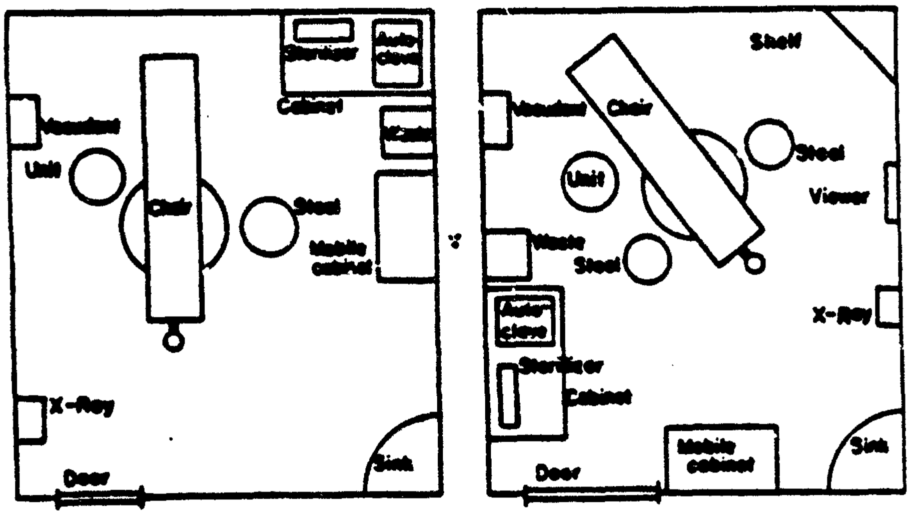
A study conducted by Green and Lynam [1958] sought to determine the extent to which work simplification techniques, primarily the principles of motion economy, could be applied to the practice of dentistry. It was stated that adherence to these principles reduced waste and effort and contributed to more effective methods and procedures which benefited both the patient and the dentist.

Dental office activities were divided into specific jobs such as oral examination, radiology, surgery, and consultation. Each job was filmed and performance times were recorded. Mundel [1958] performed a study with similar procedures and objectives which yielded similar results. In both cases, the dentist operatory areas were redesigned. Figure 3.4 illustrates the design changes as a result of Mundel's study. The revisions provided the following advantages: 1) less travel around the room by the dentist and assistant, 2) more time for dentistry during operatory periods, 3) more space for actual work, and 4) less worker fatigue due to twisting, turning, and reaching (Green and Lynam [1958] and Mundel [1958]). The objectives of the present study paralleled the objectives in both studies mentioned above.

Anderson [1960] stated that in any occupation, a motion-time study can help find a preferable procedure for doing the work. Usually there are numerous ways to perform a task (motion), and through further study, an improved method can be determined. In another study of dental office design, Anderson [1960] defined the five classes of motions listed below which were performed by dentists:

Class I: fingers only
Class II: fingers and wrist
Class III: fingers, wrist, and forearm
Class IV: full arm
Class V: gross body motion (turning, twisting, and reaching)

If the number and extent of Class IV and V motions are



Original operatory

Improved operatory

Figure 3.4 Original Dental Operatory Layout and Improved Layout (Mundel [1958])

decreased, then the overall activity is simplified and more efficient. One way to reduce the number of Class IV and V motions is to locate the primary instruments and controls in the normal work area. Figure 3.5 depicts the maximum and normal work area as defined by Sanders and McCormick [1987]. Placement of instruments outside of these areas resulted in gross bodily movements such as twisting and turning of the torso or reaching. For more efficient work patterns, these motions should be avoided.

A study done by Green and Brown [1963] was concerned with eliminating tension and fatigue in dentists. A motion study was conducted, and motions ranging from Class I to Class V were observed. Recommendations included rearranging equipment and work positions to eliminate full arm motions, reaching, trunk twisting and other class IV and V motions, as well as, becoming more physically active during work hours.

Khalil and Truscheit [1972] designed a study to evaluate and measure the effectiveness of dental operatory delivery systems. A dental operatory delivery system is made up of a therapy team and physical hardware. In an operatory environment, the hardware and therapy team form a highly integrated human-machine system. A MT study was initiated to compare the amount of time and work expended in identical operations while using different delivery configurations. Results indicated that motion-time was

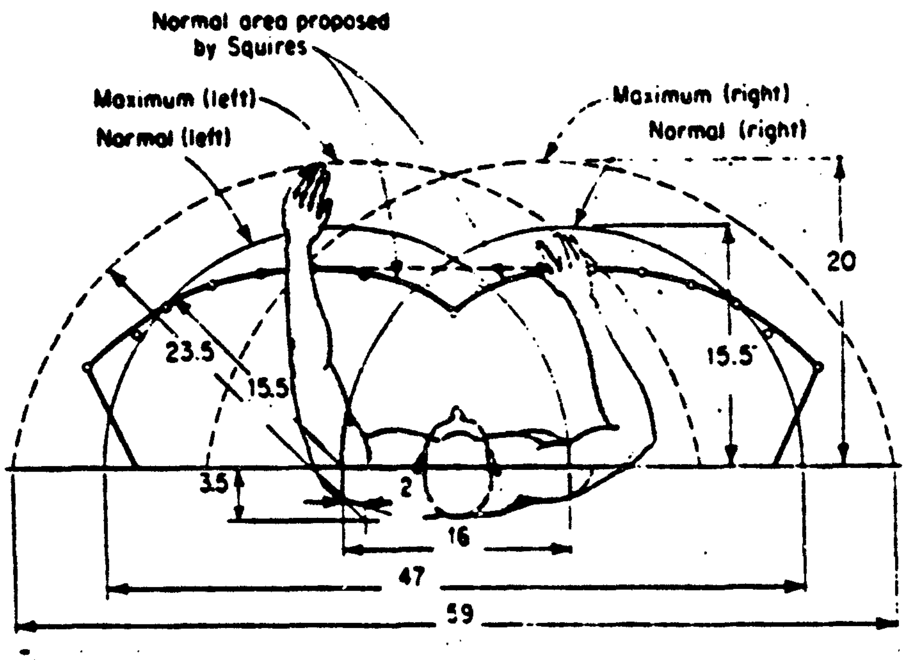


Figure 3.5 Maximum and Normal Work Area
(Sanders and McCormick [1987])

quite different among the various systems even though the operations performed were essentially the same.

Potential productivity improvements and recommended manning needs for a book binding production line were needed within six weeks. Lanier [1974] used a MT study to meet these two objectives. The activities of employees and machines were timed, and detailed explanations of employee activities during machine delays were provided. Results included pinpointing operation bottlenecks, a 15 per cent crew reduction, and better production line balancing.

The Coffee County Red Cross of Tennessee had a study done which was designed to improve bloodmobile operations (Luttrell and Wyatt [1969]). One objective of a bloodmobile is to maximize the number of blood donations. Because bloodmobile operations are typically performed by volunteers, they are not always handled efficiently. Luttrell and Wyatt [1969] ran a preliminary study and at the end recommended that a more thorough analysis be conducted. They first observed the layout of the bloodmobile operation. Then, times for each phase were determined. Queuing buildups in the operation were noted, and finally, proposed improvements in layout and utilization of nurses were provided. The time spent by each donor at each of the 10 stations was recorded, and times for each station were averaged to represent standard times. Queue buildups were noted prior to operations A and B. Buildup occurred at

operation A because donors did not adhere to the established arrival schedule. The queue buildup at operation B was attributed to the longer unit time needed to process a donor at operation B than operation A. The time needed at operation B is two and one-half times longer than the time needed for operation A. Luttrell and Wyatt [1969] also concluded that by adding three nurses at operation B, the unit time would be decreased, thus eliminating queue buildup. To reduce the amount of time required to perform any operation, equipment must be optimally located. Optimality can be achieved through the application of link analysis.

3.5 LINK ANALYSIS

Cullinane [1977] called link analysis a systematic technique for studying and planning human-machine systems. Link analysis focuses on four criteria: instrument importance, degree of relative use, similarity of function, and sequence of use (Sanders and McCormick [1987] and Sule [1988]). Morgan et al. [1963] define a link as "any connection between a man and a machine or between one man and another" (p. 322).

Lippert [1971] studied the travel patterns of nurses in a hospital. The link chart shown in Table 3.1 was constructed to show the travel patterns. The values P-1 through P-12 are patient bed numbers. From the values shown in the link chart, the mean nurse-to-patient distance and

the mean patient-bedside-to-patient-bedside distance were

	Location											
Location	P-1	P-2	P-3	P-4	P-5	P-6	P-7	P-8	P-9	P-10	P-11	P-12
Nurse Station	51	35	33	33	35	51	58	58	51	35	35	51
P-1		56	65	81	86	102	109	109	102	86	56	40
P-2			49	65	70	86	93	93	86	70	40	56
P-3				60	63	79	86	86	79	63	49	65
P-4					49	65	72	72	65	49	65	81
P-5						56	63	63	56	40	70	86
P-6							47	47	40	56	86	102
P-7								40	47	63	93	109
P-8									47	63	93	109
P-9										56	86	102
P-10											70	86
P-11												56

Table 3.1 A link chart showing travel distances (feet) between rooms at the Rochester Methodist Hospital (Lippert [1971])

computed. Lippert [1971] used these values to compare a variety of layouts.

Moore [1971] developed a computerized layout heuristic, CORELAP, which employed link data. A relationship chart was established by manually collecting link information, and these data were entered into the computer along with system parameters and constraints. The computer output included problem identification, total floor area required, an ordered table of closeness ratings, scores on every layout, and a final layout (Moore [1971]).

A unique application involving link analysis was made by Harper and Harris [1975], who constructed links of relationships among organized crime figures. Twenty-nine

police intelligence teams observed subjects for three hours each. A link diagram was constructed which summarized the observed links. From this data, the organization's structure, and the leading figure were identified. As of 1975, law enforcement intelligence officers from 10 states and Canada were using link analysis techniques with positive results.

Link analysis is a method used to determine the number and importance of links between equipment. After determining the link values for two pieces of equipment, one must decide where the equipment will be located in order to minimize motions.

3.6 PRINCIPLES OF MOTION ECONOMY

The principles of motion economy may be applied to three major areas: 1) use of the human body, 2) arrangement of the work place, and 3) design of tools and equipment. According to Barnes [1968], the principles of motion economy are not appropriate for every operation, but they do form a basis for improving the efficiency and reducing fatigue in manual work. The principles are shown in Table 3.2. If motion economy is achieved through a new design, then it is logical that energy expenditure should also be reduced.

3.7 ENERGY EXPENDITURE

Barnes [1968] stated that the objective when employing energy expenditure techniques is to design work methods so

Use of the Human Body

1. The two hands should begin as well as complete their motions at the same time. (Page 222.)
2. The two hands should not be idle at the same time except during rest periods. (Page 222.)
3. Motions of the arms should be made in opposite and symmetrical directions, and should be made simultaneously. (Page 222.)
4. Hand and body motions should be confined to the lowest classification with which it is possible to perform the work satisfactorily. (Page 235.)
5. Momentum should be employed to assist the worker wherever possible, and it should be reduced to a minimum if it must be overcome by muscular effort. (Page 237.)
6. Smooth continuous curved motions of the hands are preferable to straight-line motions involving sudden and sharp changes in direction. (Page 241.)
7. *Ballistic movements* are faster, easier, and more accurate than restricted (fixation) or "controlled" movements. (Page 245.)
8. Work should be arranged to permit easy and natural rhythm wherever possible. (Page 247.)
9. Eye fixations should be as few and as close together as possible. (Page 249.)

Arrangement of the Work Place

10. There should be a definite and fixed place for all tools and materials. (Page 256.)
11. Tools, materials, and controls should be located close to the point of use. (Page 258.)
12. Gravity feed bins and containers should be used to deliver material close to the point of use. (Page 266.)
13. Drop deliveries should be used wherever possible. (Page 271.)
14. Materials and tools should be located to permit the best sequence of motions. (Page 273.)
15. Provisions should be made for adequate conditions for seeing. Good illumination is the first requirement for satisfactory visual perception. (Page 273.)
16. The height of the work place and the chair should preferably be arranged so that alternate sitting and standing at work are easily possible. (Page 283.)
17. A chair of the type and height to permit good posture should be provided for every worker. (Page 286.)

Design of Tools and Equipment

18. The hands should be relieved of all work that can be done more advantageously by a jig, a fixture, or a foot-operated device. (Page 289.)
19. Two or more tools should be combined wherever possible. (Page 295.)
20. Tools and materials should be pre-positioned whenever possible. (Page 297.)
21. Where each finger performs some specific movement, such as in typewriting, the load should be distributed in accordance with the inherent capacities of the fingers. (Page 298.)
22. Levers, crossbars, and hand wheels should be located in such positions that the operator can manipulate them with the least change in body position and with the greatest mechanical advantage. (Page 301.)

Table 3.2 The Principles of Motion Economy
(Barnes [1968])

that the operator can perform the task eight hours per day, five days per week, without undue fatigue. To measure energy expenditure, Edholm [1967] recommended making a motion-time study in which the activities performed throughout the day, and their duration, were recorded. Brouha [1960] stated that total energy expenditure depended on two factors: First, the energy required to produce the physical work, and second, the energy spent to maintain the body function within a normal physiological state. The first is considered whenever an individual shifts from resting position to any situation where external work is produced. The second is present at rest as well as at work.

Passmore and Durnin [1955] described several of the variables which influence the amount of energy expended for various tasks. Some of the factors include: walking on an incline, walking surfaces, weight, physical condition, sex, climate, and size of load being carried.

One way to achieve motion economy, and thus reduce energy expenditure is by using design guidelines. If applied, design guidelines ensure that controls are easy to use and the work environment is comfortable for the human operator.

3.8 DESIGN GUIDELINES

Most of the design guidelines applied in this study were drawn from tables, charts, or figures found in human factors or equipment design handbooks. There exists a

wealth of literature on systems or equipment design. Some of the more notable literature is provided by Morgan et. al. [1963]. Woodson and Conover [1970], Van Cott and Kinkade [1972], Roebuck et. al. [1975], Sanders and McCormick [1987], and the United States Air Force. The guidelines provided by these authors and others are described in Chapter 4.

The application of these guidelines will result in a workstation that is designed with the human operator in mind. It was predicted that by implementing the recommended procedural and design changes, the analyst would require less time, motion, and energy than he presently requires, to setup and test in the laboratory.

Chapter 4

METHODOLOGY

4.1 SUBJECTS

One USAF government employee, who comprised the entire quantitative fit testing population in the USAF, volunteered to participate as a subject. The subject had three years experience working in the laboratory.

4.2 APPARATUS

All observations took place in the quantitative fit testing laboratory. A hand-held Sony CCD-8 video camera was used to videotape the USAFSAM analyst while in the process of testing a subject. The tape was played back via a Sony 8mm video cassette recorder. A Cronus stop-watch was used for timing purposes. To measure the distances between pieces of equipment, a Master Mechanic 30 foot tape measure was used. A mock-up was built from 1/2 inch plywood, masonite, and two inch by four inch boards. The appropriate laboratory hardware was mounted, and all plumbing connections were made, thus providing a functional mock-up of the new workstation.

4.3 PROCEDURE

To evaluate the effectiveness of the current laboratory layout, a MT study was conducted. The purpose of the MT study was explained to the subject prior to his voluntary

consent to participate. Before the MT study was run, the distances between pieces of equipment were measured. The center of each piece of equipment was determined, and measurements were taken between equipment center points. The USAFSAM analyst was videotaped as he tested a subject in the fit testing chamber. The videotape was made in the current laboratory setting. From the video, descriptions were obtained for each activity being timed. These activities were entered on an observation sheet (See Appendix B), and became the focus of the methods analysis and motion study. The observation sheet was used to record activity times during the MT study. Times for the study were obtained from the videotape. Timing procedures involved running the videotape and using a stop-watch to obtain activity times. After each activity was timed, the time was recorded in the appropriate place on the observation sheet. The process continued until all activities were timed. With this information, the time needed to setup and test were computed, and the total time was determined.

Following the time study, a motion study was conducted. The motion study consisted of two parts: 1) a methods analysis and 2) a determination of the extent to which the Principles of Motion Economy were employed in the laboratory. For the methods analysis, the activities recorded on the observation sheet were analyzed.

inefficiencies in the process were determined, and a new work method was developed. The new method is described in Chapter 6. Seven of the 22 Principles of Motion Economy proposed by Barnes [1968] were appropriate for this study and were used o evaluate the motion economy of the current design. The seven principles are defined in Table 4.1.

1. Principle four -- Hand and body motions should be confined to the lowest classification with which it is possible to perform the work satisfactorily.
2. Principle eight - Work should be arranged to permit easy and natural rhythm wherever possible.
3. Principle nine - Eye fixations should be as few and as close together as possible.
4. Principle eleven - Tools, materials, and controls should be located close to the point of use.
5. Principle sixteen - The height of the work place and the chair should preferably be arranged so that alternate sitting and standing at work are easily possible.
6. Principle seventeen - A chair of the type and height to permit good posture should be provided for every worker.
7. Principle twenty-two - Levers, crossbars, and hand wheels should be located in such positions that the operator can manipulate them with the least change in body position and with the greatest mechanical advantage.

Table 4.1 The seven principles used to analyze motion economy in the Quantitative Fit Testing Laboratory (Barnes [1968])

After completing the initial MT study, three new laboratory designs were developed. Each of the designs was evaluated based on the following criteria: time and motion

efficiency, energy expenditure, adherence to design guidelines, and link analysis.

From the evaluation of the analyst's performance in the original laboratory, it was found that an excessive amount of time was spent in the following areas: walking between equipment, plugging and unplugging equipment from electrical sources, and moving the keyboard and intercom. The time spent performing these activities was determined, and performance goals were established using a method proposed by Ozan [1966]. The equation used to compute the performance goals is:

(1)
{Original time needed to perform the entire activity} -

(2)
{Time needed to move between the pieces of equipment} +

(3)
{Time needed to move from 1 piece of equipment to the other}

Because the facility to which the Quantitative Fit Testing Laboratory was to be moved was not yet complete, it was necessary to simulate some of the characteristics of the laboratory. Geer [1981] stated that "a functional mock-up makes it possible to study the performance of personnel in simulated operational situations" (p. 168). The times used in variable (3) were determined by using a stopwatch to time simulated movements between the appropriate equipment. The features that were simulated were walking time from the workstation to the sink, the walking time from the sink to

the balance, and the walking time from the workstation to the mask storage cabinet. Tape was placed on the floor at the appropriate distance from the equipment. As the analyst proceeded normally from the workstation to the sink, from the sink to the balance, and from the workstation and booth to storage, stopwatch times were taken over the distance from the tape to the equipment piece. The times recorded from the simulation, and the times taken from the second MT study were combined to provide an overall time perspective for the analyst working in the laboratory mock-up.

The second method used to evaluate the proposed designs was the extent to which the seven Principles of Motion Economy listed in Table 4.1 were achieved. For the first principle used, there are five classifications, ranging from finger motions (Class I) to gross body motion involving turning, twisting, and reaching (Class V). This last class necessitates posture disturbance. By applying the Principles of Motion Economy to each of the design proposals, the amount of motion was reduced to the lowest level possible considering the constraints of each particular design.

Given that the amount of motion required to setup and test in each proposed design was minimized, a methods analysis was used to determine which of the proposals was most efficient. This was accomplished by doing a task-by-task comparison for the three designs. Following the

methods analysis, the amount of energy expended by the analyst was determined.

From the motion-time study, the activities performed throughout the fit testing process, and their duration, were recorded. The results were expressed as so many minutes spent walking, sitting, doing laboratory work, typing on the computer, and so on. Then, by using energy expenditure charts containing activities which were similar to those performed by the analyst, the total energy expenditure required to work in each proposed laboratory was computed.

Kennedy and Bates [1965] proposed 13 dimensions (See Figure 4.1) which are important for console design. Van Cott and Kinkade [1972] state that three other operator-related dimensional factors which should be considered are: eye position with respect to display area or field of view, reach envelope of arms and legs, and manner and position of human body support. The design proposals were evaluated based on whether or not the design met the dimensions recommended by Kennedy and Bates [1965] and Van Cott and Kinkade [1972].

Link analysis was the final area upon which the design proposals were evaluated. With help from the USAFSAM analyst, the components which were included in the workstation were determined. According to Woodson [1981], link analysis is used only after decisions have been made regarding the items which will be included on the control

Type of Console	A Maximum Console Height from Standing Surface	B Console Depth	C Vertical Dimension of Panel Including Sills	D Console Panel Angle—from Vertical	E Minimum Panel-Shelf Depth	F Minimum Writing Surface Depth—Including Panel Shelf	G Minimum Knee Clearance	H Foot Support to Seat	I Seat Adjustability	J Minimum Thigh Clearance at Midpoint of "I"	K Writing Surface Height from Standing Surface	L Seat Height at Midpoint of "I"	M Maximum Console Panel Breadth
1. Sit-stand	62.0	Opt.	26	15°	4	16	18	18	4	6.5	36.0	28.5	36
2. Sit (with vision over top)	47.5[a] to 53.0	Opt.	22	15°	4	16	18	18	4	6.5	25.5 to 26.0	18.0 to 28.5	36
3. Sit (without vision over top)	51.5[b] to 62.0	Opt.	26	15°	4	16	18	18	4	6.5	25.5 to 26.0	18.0 to 28.5	36
4. Stand (with vision over top)	62.0	Opt.	26	15°	4	16	—	—	—	—	36.0	—	36
5. Stand (without vision over top)	72.0	Opt.	26	15°	4	16	—	—	—	—	36.0	—	36

[a] "A" must never be more than 29.5 in. greater than "L."
[b] "A" must never be more than 33.5 in. greater than "L."

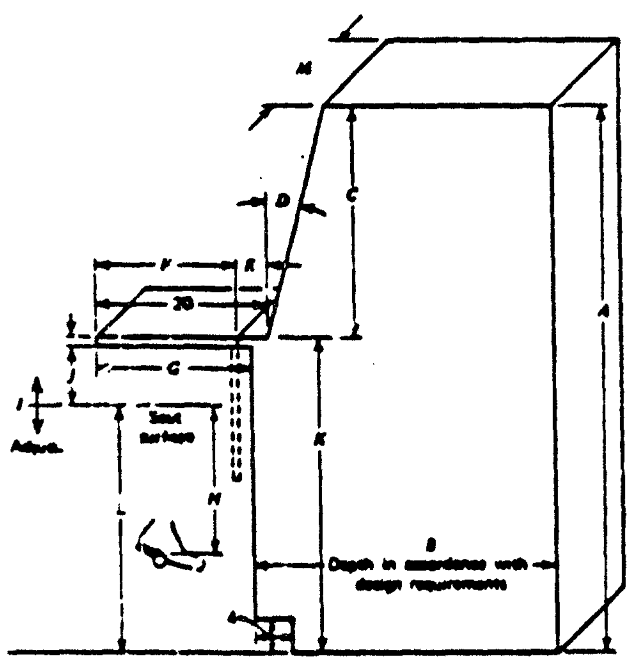


Figure 4.1 Thirteen Dimensions that are Important for Console Design (Roebuck et. al. [1975])

panel. One exception in the Quantitative Fit Testing Laboratory was the fit testing chamber (booth). For this study, the booth was included in the link chart although it was not a part of the control panel. This was necessary because the booth was a vital part of the fit testing process; air flow lines must be as short as possible to reduce calibration errors.

The link chart served as one input when decisions were made regarding equipment placement. Link data indicated how often components were linked and the importance of the links. The analyst rated the importance of each link. The types of links used were communication links (auditory), control links, and movement links (eye and body movements). Link analysis was the final evaluation method used to determine the best design proposal.

The best laboratory design was determined from the three proposals, and a mock-up of that design was built. Using the mock-up, a second MT study, energy expenditure analysis, design guideline analysis, and link analysis were conducted. A cost and worker output analysis were also conducted, and a questionnaire was administered. The results obtained using the mock-up were then compared to the results from evaluations of the current laboratory. The two layouts and work methods were evaluated to determine whether the design developed in this project was better than the layout currently used.

Chapter 5

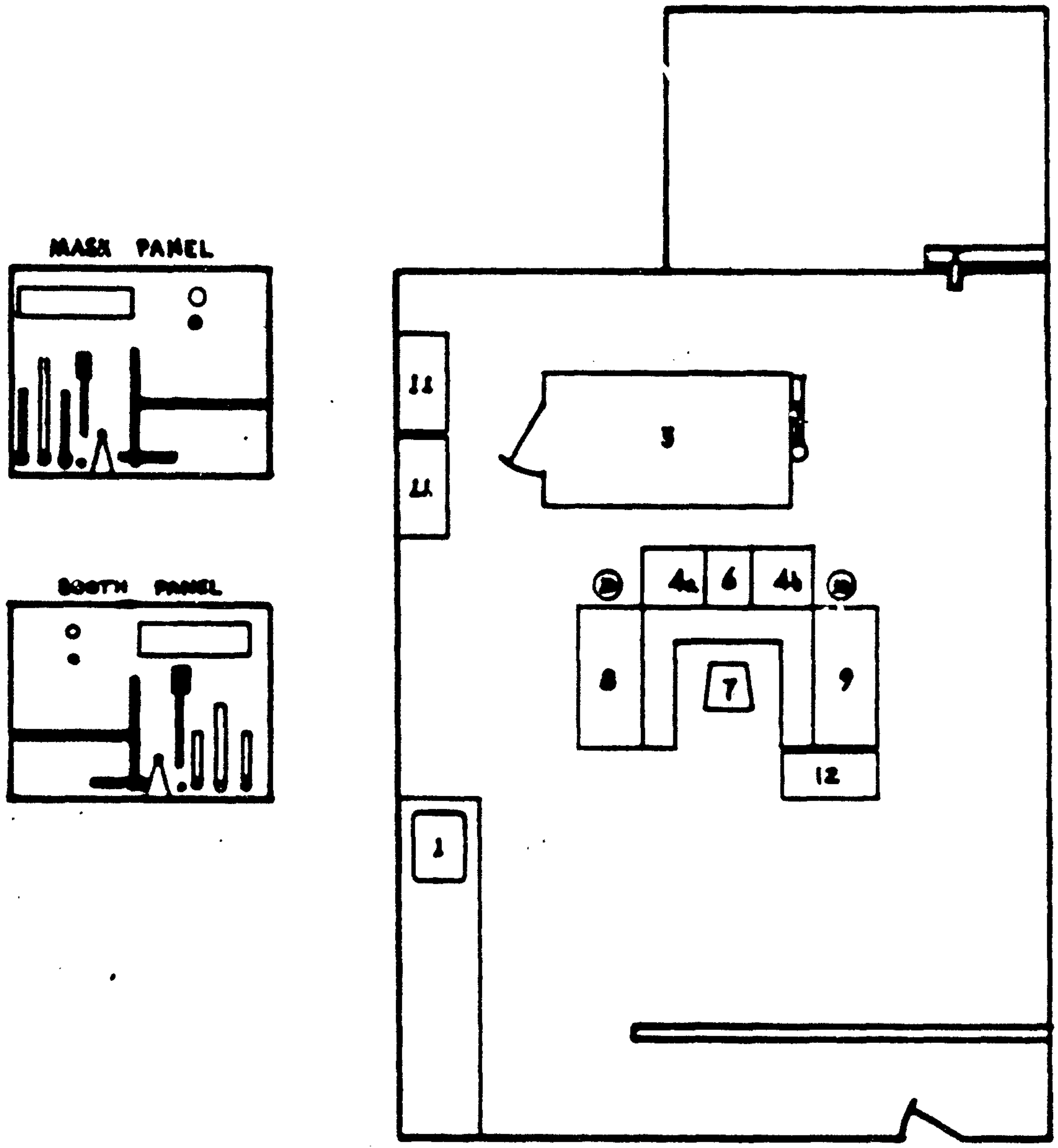
A DESCRIPTION OF THE THREE PROPOSED LAYOUTS

5.1 A DESCRIPTION OF DESIGN ONE

In this chapter, three alternative designs are presented. The first design described is D1. In addition to the specified system objectives, another objective of D1 was to locate the equipment closer to the analyst. Figure 5.1 indicates that with a wrap-around console the control panels were easier to reach. In fact, the air flow instruments were located less than three feet from the chair (7). The entire workstation was located approximately six to eight feet from the sink (1), and the booth panel (8) and the mask panel (9) were located approximately three feet from the booth (3). Another feature of D1, was the closeness of the storage cabinets (11) to the booth (3). The panels were on opposite sides of the workstation, meaning that after calibrating the mask instruments, the analyst had to physically move to the booth panel to calibrate the booth instruments. In D1, the equipment was located relatively close to the analyst, with no wires and pipes protruding into the walkway. Finally, to unclutter the work area, the computer printer was located on a printer stand (12).

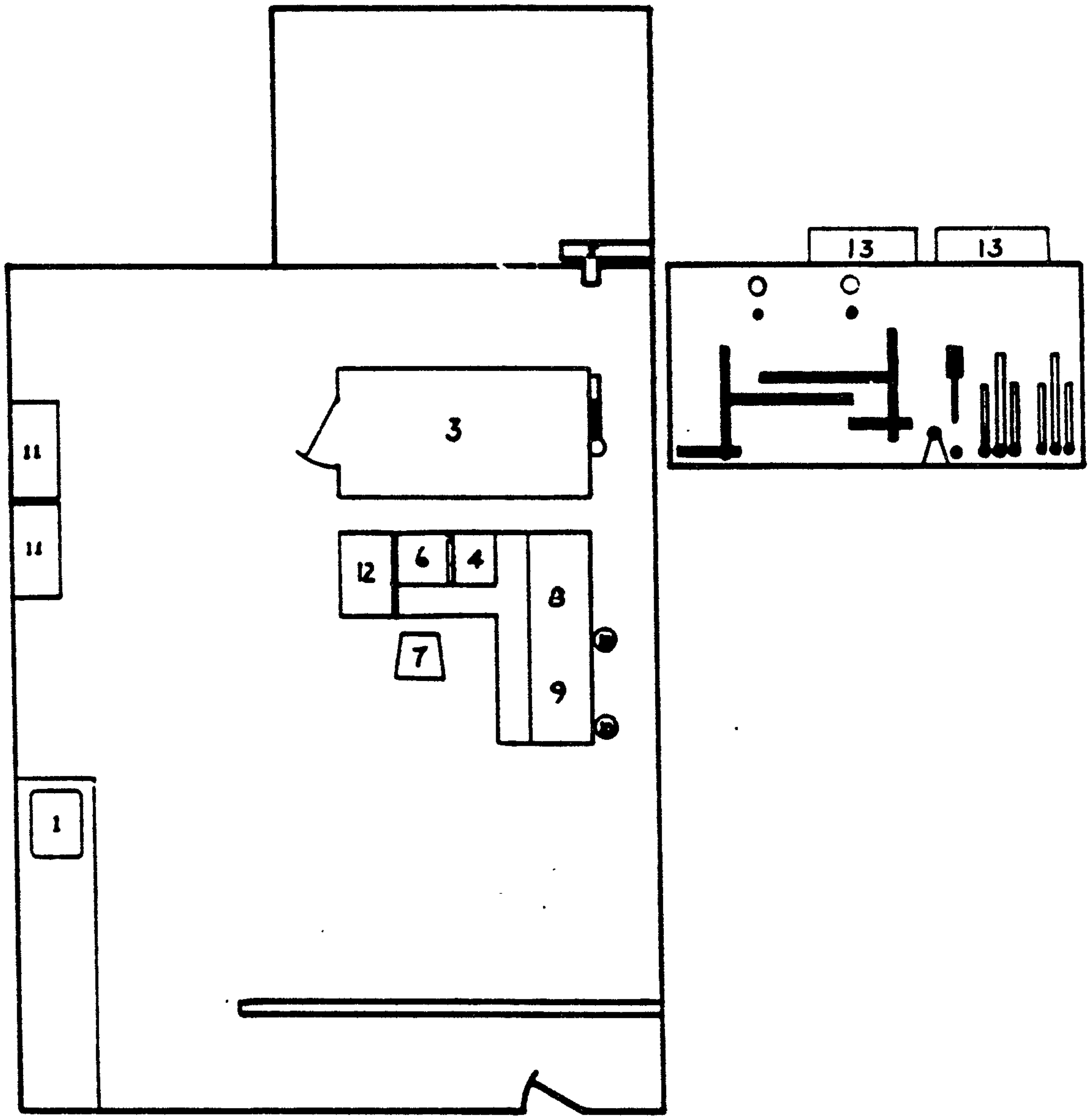
5.2 A DESCRIPTION OF DESIGN TWO

The layout for design two (D2) is shown in Figure 5.2.



1: Sink
2: Extra Equipment
3: Fit Testing Booth
4a: Integrator Box and Data Logger
4b: Integrator Box and Disk Drive
5: Air Source
6: Computer
7: Chair
8: Booth Panel
9: Mask Panel
10: Hydrogen
11: Storage Cabinets
12: Printer Stand

Figure 5.1 The Equipment Layout for Proposed Design One



1:	Sink	7:	Chair
2:	Extra Equipment	8:	Booth Panel
3:	Fit Testing Booth	9:	Mask Panel
4a:	Integrator Box and Data Logger	10:	Hydrogen
4b:	Integrator Box and Disk Drive	11:	Storage Cabinets
5:	Air Source	12:	Printer Stand
6:	Computer	13:	DC Power Source

Figure 5.2 The Equipment Layout for Proposed Design Two

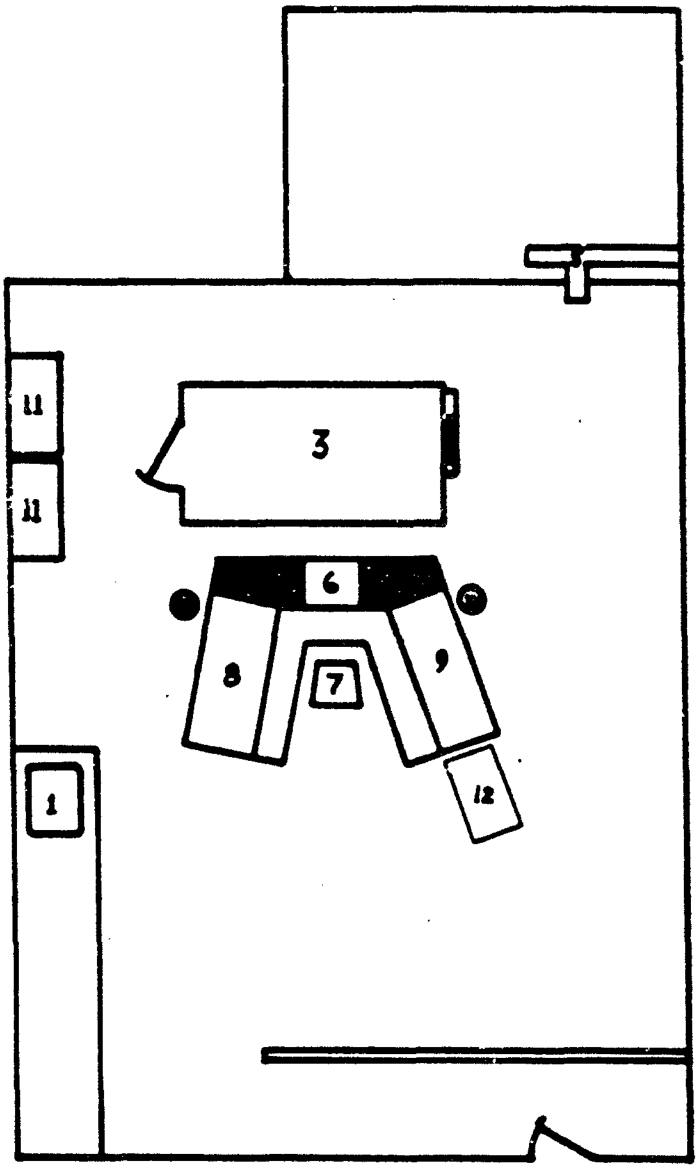
D2 was different from either of the other two designs. D1 and D3 had wrap-around consoles, but D2 had an L-shaped console. An additional objective of D2 was to have the workstation more open. In D2, the workstation was further away from the sink (1) and storage cabinets (11) than in D1. Again, protruding pipes and wires were not a problem. Only one control panel was required. The panel contained instruments for both the mask and booth, so the analyst did not have to move in the chair during calibration. In order to make room for all of the instruments, the DC power sources (13) were located on top of the panel. To unclutter the work area, the computer printer and data logger were located on a printer stand (12).

5.3 A DESCRIPTION OF DESIGN THREE

The layout for design three (D3) is shown Figure 5.3. The control panels for D3 are shown in Figures 6.2 and 6.3 on pages 55 and 56. D3 offered a spatial compromise between D1 and D2. The air flow instruments were closer to the analyst in D3 than in either of the previous two designs. Similar to D1 though, the workstation was located close to the sink and storage cabinets. The printer and data logger were located outside of the workstation in an attempt to unclutter the work area, and protruding pipes and wires were not a problem.

5.4 OTHER DESIGN CONSIDERATIONS

In each design, the three air flow instruments were



1: Sink
2: Extra Equipment
3: Fit Testing Booth
4a: Integrator Box and Data Logger
4b: Integrator Box and Disk Drive
5: Air Source
6: Computer
7: Chair
8: Booth Panel
9: Mask Panel
10: Hydrogen
11: Storage Cabinets
12: Printer Stand

Figure 5.3 The Equipment Layout for Proposed Design Three

located together based on the Functional Grouping Principle defined by Goldbeck et. al. [1971]. This principle states that controls and displays with the same mission should be grouped together. Goldbeck et. al. [1971] also define the Location-by-Frequency Principle in which the more frequently used controls and displays are placed in optimum locations on the panel. For D1 and D3, this principle was followed.

Another design consideration was labeling. Labeling is an effective way to identify controls and displays which helps to eliminate confusion between equipment. For the proposed designs, the same labeling scheme was used. All labels were located above each display or control. In Figure 6.3, on page 56, the calibration line label was misplaced, but was correctly placed prior to testing. Additional labels were placed on wires and air flow lines on the back side of the panel for identification purposes during maintenance. Woodson and Conover [1970] stated that all labels should be consistently placed above or below the accompanying display, with above being the preferred location. The manometer hydrogen pressure, the line air pressure, the DC power source, and the integrator box contain permanent labels on the face of each display.

Lighting was another design consideration. Bogue [1949] stated that lighting intensity in different laboratories varied from 15 to 38 foot-candles, and researchers prefer an intensity of 30 foot-candles.

Blanchard and Fabrycky [1981] recommended levels somewhat higher than that previously mentioned. For panels, dials, and rough inspection tasks, the recommended illumination level was 50 foot-candles, with 30 foot-candles being the recommended minimum. Accordingly, a light intensity of 50 foot-candles was recommended for the new laboratory facility.

Finally, a shelf, which ran along the inside of each workstation, was provided, to allow the analyst to rest his forearm while using the controls and typing on the keyboard. Electrical outlets were provided on the front of each control panel which enabled the analyst to easily plug and unplug the pumps when necessary.

Chapter 6

RESULTS

6.1 OVERVIEW

The three proposed designs were evaluated in each of the following areas: time efficiency, adherence to the Principles of Motion Economy, work methods, energy expenditure, link analysis, and applicability of design guidelines. Of the three proposals, D3 was deemed the best. Figure 6.1 shows the focal point of D3. The computer and both sets of air flow instruments are shown. The mask panel is shown in Figure 6.2, and the booth panel is shown in Figure 6.3.

6.2 TIME COMPARISON FOR THE PROPOSED DESIGNS

Because each of the proposed designs was not actually tested, performance goals were computed and used as described in Chapter 4. These performance goals served as the anticipated times for setup and testing in each of the design proposals. Using the anticipated times, comparisons were made among designs. For the three proposals, the anticipated time reduction during setup was 4.10 minutes, the time reduction during testing was .86 minutes, hence, the total time reduction was expected to be 4.96 minutes. The time reductions were possible because, in each design, the entire workstation was closer to the sink, the booth was closer to storage, and the consoles were moved almost to

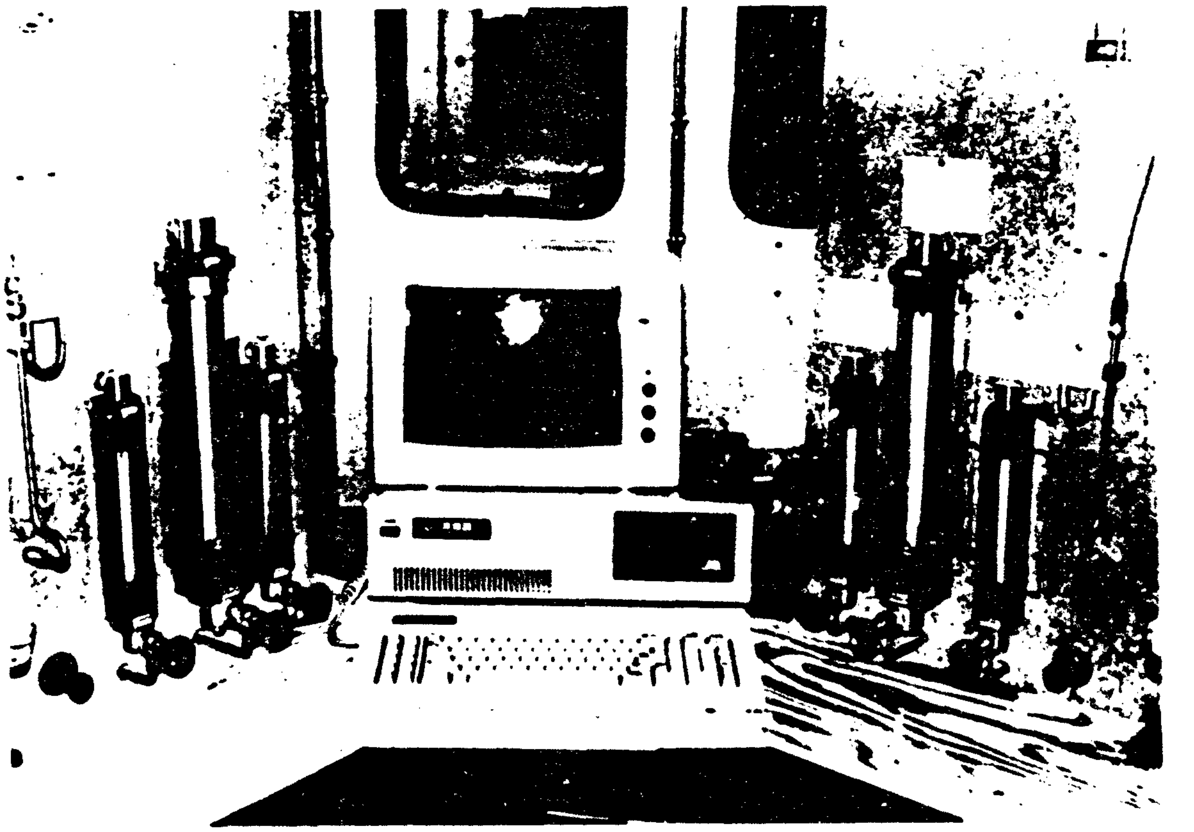


Figure 6.1 The Focal Point of the D3 Mock-up Showing the Computer and Air Flow Instruments

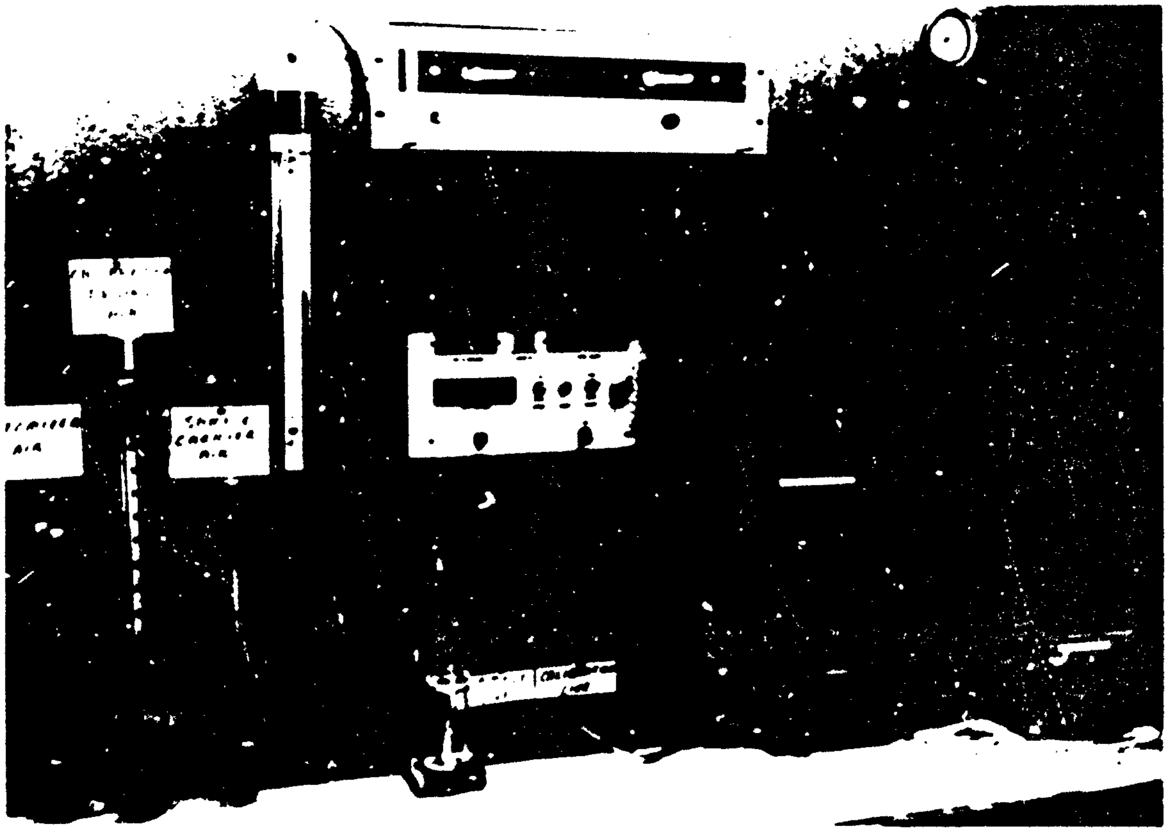


Figure 6.2 The Mast Panel for the D3 Mock-up

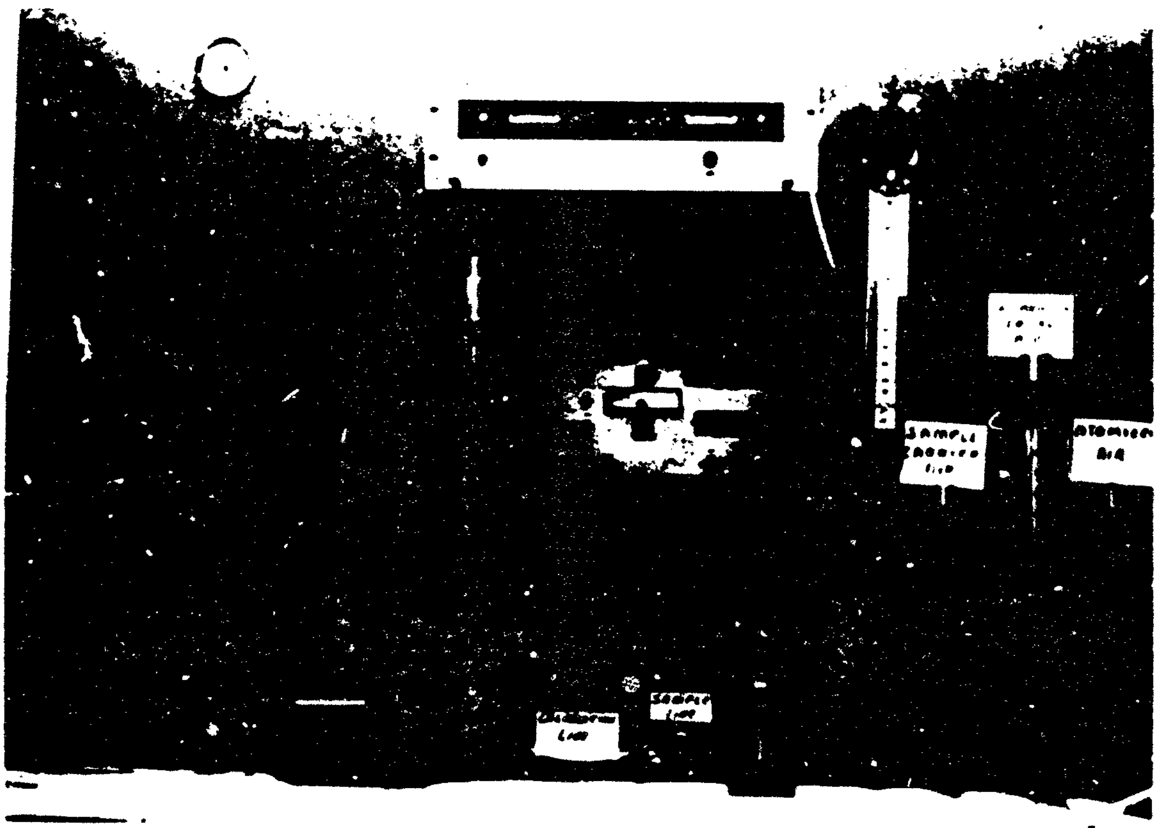


Figure 6.3 The Booth Panel for the D3 Mock-up

within arms reach of the analyst, thus eliminating walking between the computer and the consoles. With D3, it was expected that the potential time reductions would be similar, but greater, than those anticipated in D1 and D2. This was probable because in D3, the controls were all located within 21 inches of the analyst, thus requiring a short arm movement to reach the desired control. In D1, the analyst had to extend his arm and lean to the side to make control inputs. In D2, the analyst had to move the chair approximately two feet and extend his arm.

6.3 A COMPARISON OF THE PRINCIPLES OF MOTION ECONOMY

The first Principle of Motion Economy states that motions should be confined to the lowest classification possible. There are five classifications, ranging from finger motions (Class I) to gross body motion involving turning, twisting, and reaching (Class V). In D3, a Class III motion was required to manipulate the most frequently used controls. Motions in the other two designs exceeded a Class III motion.

The second principle states that work should be arranged to permit an easy natural rhythm wherever possible. D3 allows for an easy natural rhythm for two reasons. First, the analyst could comfortably rest his forearms on the shelf and still easily reach the controls. In the other designs, more drastic movements were necessary to reach the controls. Second, in D3, all of the controls were located

within a 35 degree arc to either side of the computer (which is in the center), so the analyst could rhythmically move back and forth from the booth instruments to the mask instruments.

The third principle states that eye fixations should be as few and as close together as possible. D3, again, was the most economical design. Morgan et. al. [1963] stated that the maximum viewing angle with the eye is 35 degrees. With the frequently used instruments located within 35 degrees to either side, eye fixations were relatively close together in D3. Controls in D1 and D2 were located well beyond 35 degrees.

The fourth principle applies the same for each of the designs. This principle states that tools, materials, and controls should be located close to the point of use. In each design, the sink and storage cabinet were approximately the same distance from the workstation, however, the distinguishing characteristic was the arm reach distance to the air flow instruments. In D3, arm reach to the furthest instrument was only 21 inches, while in D1 and D2 this distance was much greater.

Principle five states that the height of the work place and the chair should be preferably arranged so that alternate sitting and standing at work are easily possible. The height of the work place was identical for all three designs, 29 inches. This was lower than the 36 inches

recommended by Kennedy and Bates [1965], for a couple reasons: 1) the analyst sits most of the time and 2) line-of-sight over the top of the computer was necessary from the sitting position.

Principle six states that the use of a chair of the type and height to permit good posture should be provided. A chair with casters on the bottom, an adjustable back support, and adjustable height was recommended for all three designs. The chair is shown in Figure 6.4.

The final principle which was addressed states that levers, crossbars, and hand wheels should be located so that they can be manipulated with the least change in body position and with the greatest mechanical advantage. D3 was clearly the most motion efficient. The largest class of motion routinely required in D3 was Class III. The summary rankings of each design for each of the Principles of Motion Economy are provided in Table 6.1. The ranking scale went from one to three, with a one symbolizing the design which best fulfilled the intent of the principle.

6.4 COMPARISON OF THE WORK METHODS FOR THE PROPOSED DESIGNS

An evaluation of the work methods was conducted following the first MT study. From the evaluation, several inefficiencies were found, and a new method was developed. Because the same method was used in each design, the differences between designs was not great, however, differences did exist.

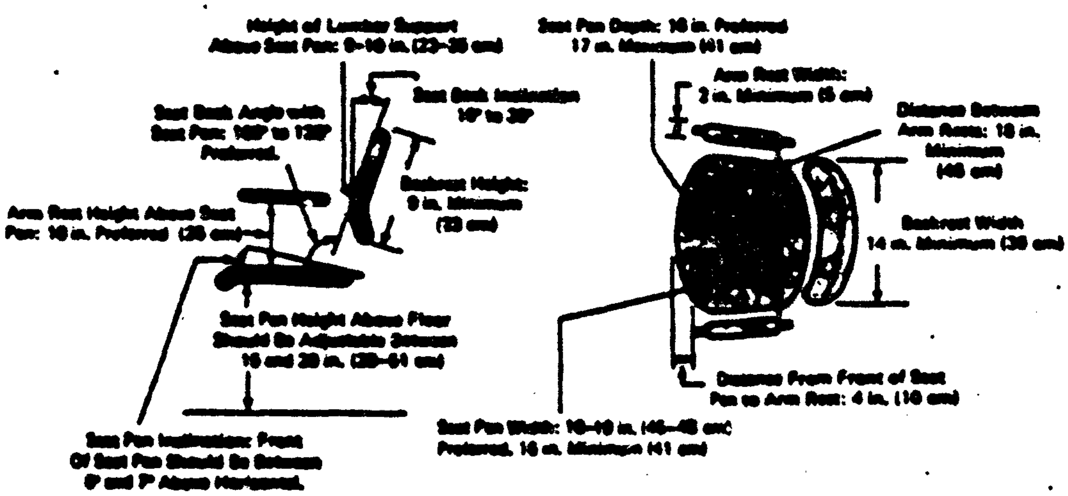


Figure 6.4 The Chair Recommended for Use in the Quantitative Fit Testing Laboratory (Sanders and McCormick [1987])

Principle	D1	D2	D3
Hand & body motions confined to lowest class necessary to perform task	Mainly Class V motions (2)	Movement in the chair, then Class II-III motions (3)*	Class III motions (1)
Work arranged to allow natural rhythm	Some rhythm possible (2)	No rhythm possible (3)	Rhythm easy to establish (1)
Eye fixations are few & close together (to computer and air flow instruments)	Viewing angle 50-60 degrees (3)	Movement in chair, then viewing angle ~45 degrees (2)	Viewing angle 35 degrees (1)
Tools & controls located close to point of use (Air flow instruments)	Arm reach is 32 inches (2)	Movement in chair, then arm reach is 16 inches (3)	Arm reach 21 inches (1)
Height of workplace & chair arranged to allow standing & sitting	Same for each design		
Chair permits good posture	Same chair used for each design		
Controls located so that manipulation can be accomplished with least change in body position	Class V motion required (2)	Movement in chair, then Class II-III motions (3)*	Class III motions (1)

* Only Class II-III motions are necessary to manipulate the controls, but the body motion necessary to move the chair to the controls makes the ranking for these principles lower

Table 6.1 Summary table for the Principles of Motion Economy

A hypothetical functional flow diagram was constructed for each of the designs and was converted to the tables shown in Appendices C, D, and E, for D1, D2, and D3 respectively. From the tables, a methods analysis was conducted. By projecting the use of the improved methods into D1, D2, and D3, a comparison was made among designs. Results of the comparison revealed that D3 was the most advantageous design to use in order to economize motion. A final evaluation of the motions performed in D3 showed that the first eight steps were identical to the first eight steps used in D1 and D2. In Step nine of D3, the analyst had to turn in the chair, while in the other designs the analyst had to turn and move in the chair. In Step 10, D2 required the least movement because the calibration instruments were located together on the same control panel. Steps 12 through 17 were identical for each design. In Steps 18, 19, 23, and 24, D3 was the most motion efficient; the analyst merely had to perform a Class III motion to adjust the air flows. Steps 21, 22, and 25-33 were identical. By implementing the new recommended work sequence in D3, motion was minimized. In Table 6.2, each of the designs is ranked based on the amount of motion required to perform the step. A one indicated the design in which the least amount of motion was required to perform the step.

From the table, it is obvious that the motions required were quite different among the three designs even though the

Steps Required to Setup & Test	D1	D2	D3
Steps 1-9	Same for each design		
Step 10	Sliding movement in chair (3)	No movement required (1)	180 degree turn in chair (2)
Step 11	Sliding movement in chair (2)	Sliding movement in chair (2)	90 degree turn in chair (1)
Steps 12-17	Same for each design		
Steps 18-20	Turn & reach movement (2)	Sliding movement in chair (3)	Reach movement (1)
Steps 21-22	Same for each design		
Steps 23-24	Turn & reach movement chair (3)	Sliding movement in chair (1)	Reach movement (2)
Steps 25-33	Same for each design		
Walking distance	166 feet (2)	180 feet (3)	134 feet (1)

Table 6.2 Summary table for methods analysis

operations performed were essentially the same. By being the most motion efficient, D3 was bound to reduce energy consumption.

6.5 A COMPARISON OF ENERGY EXPENDITURE FOR D1, D2, AND D3

Using information taken from Konz [1979] and Woodson [1981], it was determined that while working in a laboratory designed such as D1, the analyst would expend approximately

118.52 kcal/hour. In D2, the analyst would expend 119.87 kcal/hour, and while working in D3, the analyst would expend 118.43 kcal/hour. The computed energy expenditures for each design were then multiplied by eight, to show the total energy expenditure for a work day in which an average of eight subjects were tested. The results are shown in Table 6.3. The differences found between the designs was insignificant, but these results were one more piece of evidence which showed that D3 was the best design.

Design	Energy Expenditure (kcal/day)
Design one	948.16
Design two	958.96
Design three	947.44

Table 6.3 Summary table of energy expenditure for an eight hour work day

6.6 A COMPARISON OF LINK ANALYSIS FOR THE PROPOSED DESIGNS

The link chart is shown in Figure 6.5. The numbers in the link chart indicated the number of times the two pieces of equipment wer linked during setup and testing. In this project, only the A, E, and I links were addressed. The lengths of these links were used for evaluation purposes. The purpose for using link data was to ensure that equipment pieces that had to be located close together were located as close together as possible. Closeness does not ensure efficient movement between the equipment, but it is one way to evaluate the link values. A summary of the A, E, and I

Each of the letters below indicates how essential it is for two pieces of equipment to be located close together. The number indicates how often the two pieces of equipment are linked.

Key

A: Absolutely
E: Essential
I: Important
O: Ordinary closeness
U: Unimportant

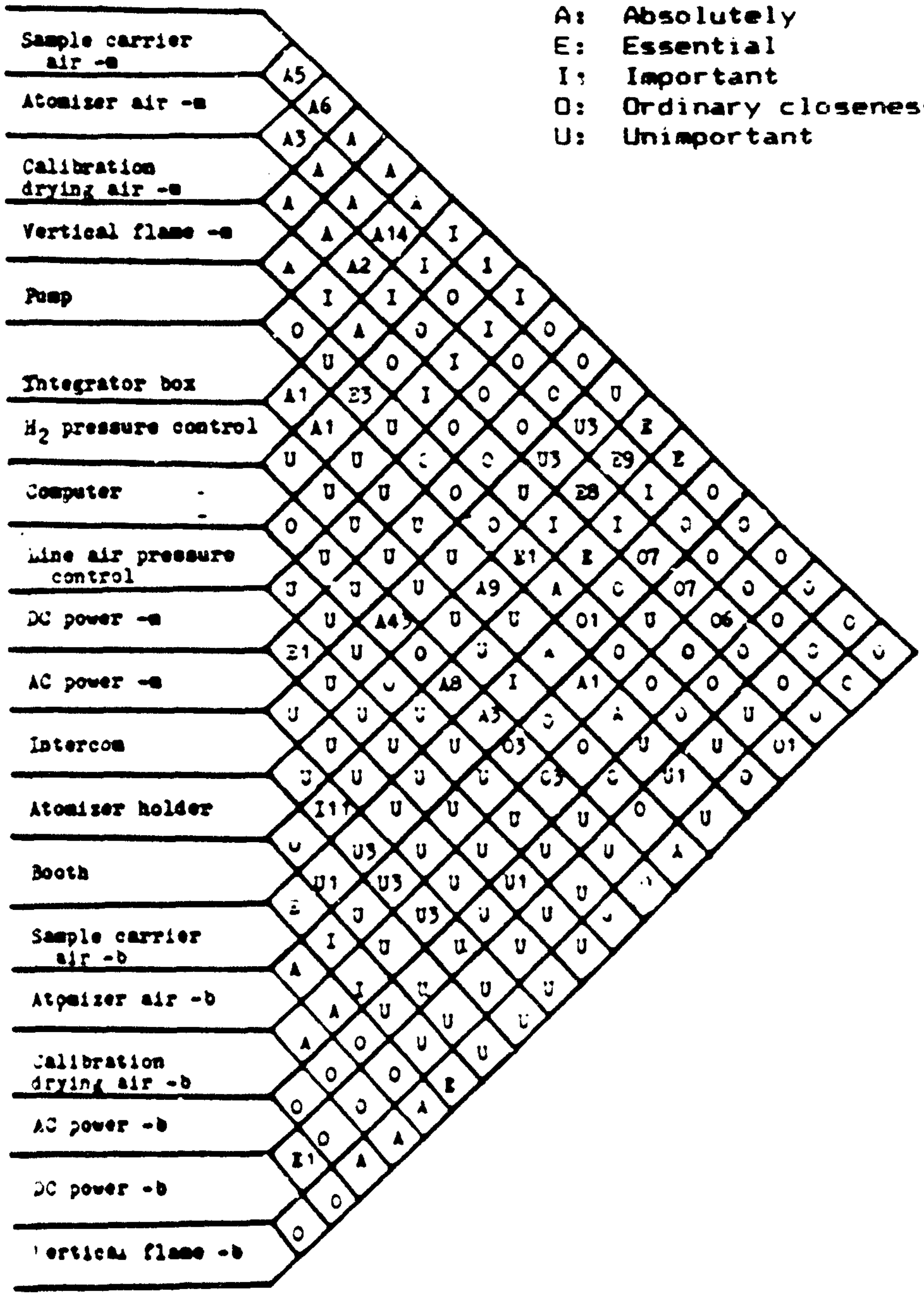


Figure 6.5 Link Chart of the Quantitative Fit Testing Laboratory (b - booth and m - mask)

link distances is shown in Table 6.4. The table clearly shows that D3 is the best design based on link distances.

	"A" link	"E" link	"I" link
D1	2.5	5.5	3.5
D2	3.5	6.5	7.5
D3	2.5	4.0	3.0

Table 6.4 Summary of the link lengths (feet) for each design

6.7 DESIGN GUIDELINES

Kennedy and Bates [1965] described 13 dimensions (See Figure 4.1 on page 44) which were important for console design. The console required in the Quantitative Fit Testing Laboratory was a sit-stand console in which vision over the top of the computer was necessary. The 13 dimensions were the focus of the design guideline evaluation. A summary of the dimensions for each design, and the rankings of each design on that dimension are shown in Table 6.5. For most of the dimensions, the three proposals were the same. In the first dimension, D2 was rated the best because the console height did not come into play for this design. The computer sat at approximately 30 inches above the floor, and the control panel was located two feet from a wall, so there was no need to see over the top of the console. For the third dimension, D1 was rated the best. Due to its shape, the front portion of the workstation accommodated more equipment than the front part of either D2 or D3. Therefore, the height of the side

Dimension	D1	D2	D3
Max. console height from standing	62" over side panels (2)	Panel located against wall (1)	65" over side panels (3)
Console depth	Same for each design		
Vertical panel dimension	33" (1)	36" (2)	36" (2)
Panel angle from vertical	The console panel angle for each design was 90 degrees		
Minimum pencil shelf depth	12 inches for each design		
Minimum writing depth	Same for each design		
Knee Clearance	Same for each design		
Foot support to seat height	Same for each design		
Seat adjust.	Same for each design		
Minimum thigh clearance	Same for each design		
Writing surface height standing	Same for each design		
Seat height	Same for each design		
Max. console panel breadth	66" (2)	80" (3)	48" (1)
Eye position with respect to field of view	LOS is 25 deg. to the VDT viewing angle to air flow displays is 51-65 degrees (3)	LOS is 15 deg viewing angle to the air flow displays is +5 degrees (2)	LOS is 15 deg., view. angle to air flow displays is 23-15 deg. (1)
Reach envelope of arms	28-32" (2)	~16" (3)	18.5-21" (1)
Body support position	Same for each design		

Table 6.5 Summary table for the design guidelines

panels was reduced because not as much equipment was placed to the side. For the maximum console panel breadth, D3 was rated the best with a breadth of 48 inches. D3 was also rated the best for the eye position with respect to the field of vision, and the arm reach envelope. The most frequently used controls were located within a 35 degree arc and 21 inches of the computer. For D2, the reach distance was only 10 inches, however, the analyst had to move in his chair to get that close. Based on the design guideline evaluation, D3 was determined to be the best. The dimensions of D3 were then compared to the dimensions recommended by Kennedy and Bates [1965]. D3 did not meet the following recommended guidelines: A, C, F, and M (See Figure 4.1 on page 44). For Guideline A, the side panels in D3 were 65 inches high, which exceeded the maximum recommended height of 58 inches. The added console height was necessary for two reasons. First, by locating some of the instruments lower on the panel, excessive plumbing costs would have resulted. All of the instruments shown on the console were connected to each other, to the booth, or to the mask. They were connected by copper tubing or rubber air flow hoses. If the console height was reduced, then to compensate, the panel would have to be extended horizontally, thus requiring excess plumbing. The second reason for the excess console height was to avoid locating equipment in the area labeled "least desirable" in Figure

6.6. In D3, the computer, keyboard, and intercom were located in the region labeled "optimum", and the remaining equipment were located in the areas labeled "acceptable". Therefore, a trade-off was made while designing D3, and the console height was 65 inches. Due to the two reasons stated above, Guidelines C and M were also not followed.

The recommended minimum writing surface depth, including the pencil shelf (Guideline F), is 16 inches. Although some writing was necessary in the workstation, the most important function was performed with the keyboard which required about 10 inches. The writing performed by the analyst was done in a six inch by nine inch steno-pad as readings were taken from the integrator box. When using the steno-pad, a 12 inch pencil shelf was adequate.

It is important to note that none of the leg clearance dimensions were applicable because the workstation had legs instead of a solid base, which might hinder leg movement. Also, the chair, which was recommended, met all of the guidelines described. Other important dimensions found in D3 included: the writing surface height (Guideline K) which was 29 inches, and the viewing angle to the computer screen which was 15 degrees below normal line-of-sight with a viewing distance of 21 inches. Sanders and McCormick [1987] stated that a viewing distance of 15-30 inches for VDT workstations is acceptable.

The design guidelines were an important part of the

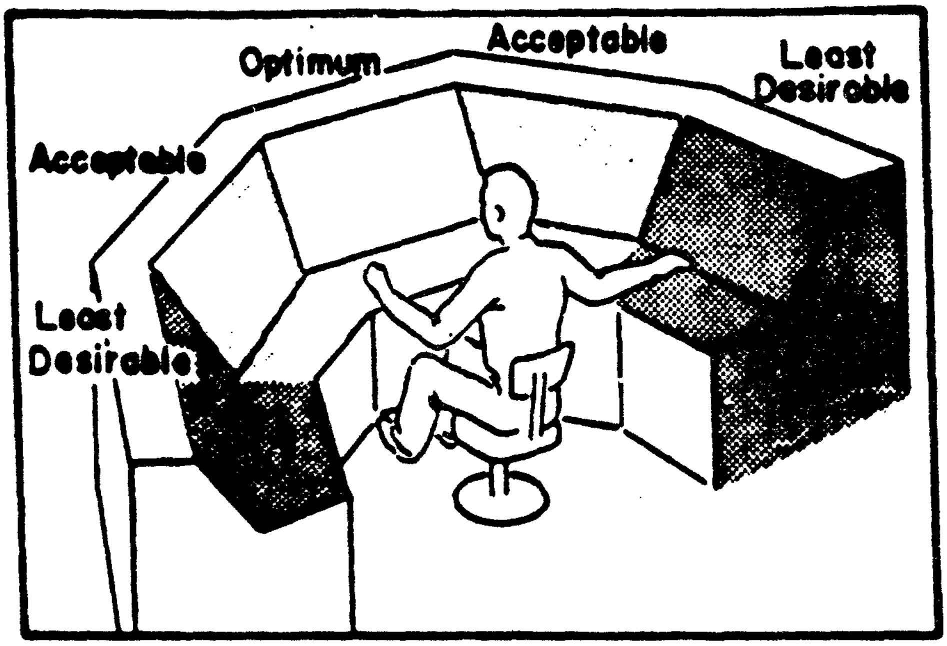


Figure 6.6 Areas Recommended to Locate Controls
in a Wrap-Around Console
(Ely et. al. [1956])

design proposal evaluations. A summary of all six evaluations is provided in Table 6.6.

1= Best 2 = Second best 3 = Worst

	Design 1	Design 2	Design 3
Link Analysis	2	3	1
Time Efficiency	2	3	1
Methods Analysis	2	3	1
Motion Econ. Principles	2	3	1
Energy Expenditure	2	3	1
Design Guidelines	2	3	1

Table 6.6 Design rankings in each of the evaluation categories

Table 6.6 clearly indicates that D3 is the best alternative. Although for several of the rating categories the differences between D3 and D1 were minimal, it was the overall superiority of D3 that made it the best design.

Having established that D3 was the best proposal, a mock-up of D3 was constructed for two reasons: 1) to test the feasibility of D3 in the laboratory setting and 2) to compare D3 to the current laboratory. A second MT study was used to determine if the layout and work methods proposed in this project were superior to the layout and work methods currently used in the Quantitative Fit Testing Laboratory.

6.8 COMPARISON OF DESIGN THREE AND THE CURRENT LABORATORY

The times obtained in the MT studies for the current

design and design three are shown in Appendix F. Also provided are the setup, testing, and total times for each. By using the suggested work method with the mock-up, the analyst was able to reduce the laboratory setup time from 48.97 minutes to 44.20 minutes. The testing time was reduced from 9.74 minutes to 8.57 minutes. The total time reduction was 5.94 minutes. This is a 10.1 per cent reduction in time.

Some significant time differences between the two designs were found in several steps. Based on a change in work methods, the analyst was able to reduce the time needed to perform Step four by .33 minutes. The time needed to perform Step 10 in the current laboratory was .26 minutes shorter than the time required in D3. This was due to the added walking distance from the workstation to the back of the booth in D3. In order to locate the workstation closer to the sink in D3, the walking distance to the back of the booth had to be lengthened. However, the walking distance to the sink was reduced. The sink was used more frequently, therefore, it was given higher priority. In Step 11, the time was reduced almost one minute in D3 because the workstation and the balance were located closer to the sink. In Step 12, the time was reduced over two minutes in D3 because most of the walking during calibration was reduced. In Step 22 for D3, the intercom was permanently plugged in, and the analyst was already sitting in the chair, so the execution time was reduced to only .001 minutes. In Step

32, time was saved because the analyst was no longer required to walk arround to the back of the console to unplug the pump. An electrical outlet was provided in the front of the workstation. The amount of time saved was better than anticipated.

Concerning the Principles of Motion Economy, D3 was the better design. In the current laboratory, the analyst performs many Class V motions, but in the D3 most of the motions are Class III motions. Also, in D3, the analyst can easily establish a rhythm while working, but because the equipment is so spread out in the current laboratory, a rhythm is difficult to generate. Eye fixations are within a 35 degree arc of the computer in D3, but they are numerous and spread out in the current laboratory. Possibly the best feature of D3 is the proximity of the equipment: frequently used instruments are within arms reach, and in the current laboratory, this same equipment is located several feet away. Alternate sitting and standing is possible in both laboratories, but the equipment height makes sitting and standing more advantageous in D3. The same chair was used for both designs, however, the chair recommended in D3 will permit better posture. Finally, D3 requires fewer changes in body position while working, than is required in the current laboratory.

From the methods analysis, the walking distance required to [illegible] and test in D3 was reduced by 73 per cent.

The reduction was accomplished by combining procedures which eliminated redundancies in the process.

Because the proposed work method was more efficient, energy expenditure was reduced over 100 kcal/day; from 1049.28 kcal/day in the current laboratory to 947.44 kcal/day in D3.

Equipment in the current laboratory is not located on a console, therefore, a design guideline comparison with D3 is not possible. The wrap-around console described in Chapter 5 was used to design D3, and the appropriate equipment was located on the control panels. Without a direct comparison between the two designs, it is still important to note that the equipment could be more conveniently located as shown in D3.

In the current layout the control panels were located on opposite sides of the laboratory, and in D3 the control panels were located on the console. The link values for D3 were much shorter than the link values for the current laboratory. Table 6.8 provides a summary comparison of the A, E, and I links for the two designs.

	"A" link	"E" link	"I" link
Current Design	6.0	8.5	8.5
Design Three	2.5	4.0	3.0

Table 6.7 Summary of the link lengths (feet) for the current laboratory and laboratory design three

6.9 COST SAVINGS AND WORKER OUTPUT

By applying current wage information and the results obtained from the second MT study, the cost savings that would result by implementing D3 can be calculated.

Setup occurred once each day, so 4.77 minutes were saved. Typically, eight subjects were tested each day. Each subject was tested while wearing three masks. The amount of time saved testing each mask was 1.17 minutes. Therefore,

(1.17 minutes saved/test)(3 tests/subject)(8 subjects/day) =

28.1 minutes saved/day (testing)

By adding the setup time savings, the total time savings per day was:

28.1 minutes + 4.77 minutes = 32.9 minutes saved/day

USAFSAM tests subjects in the Quantitative Fit Testing Laboratory 90 days per year. Thus, the time savings per year was:

(32.9 minutes saved/day)(90 days/year) =

2,961 minutes saved/year

The number of hours in 2,961 minutes was equal to:

2,961 minutes/60 minutes = 49.4 hours

According to the USAFSAM analyst who conducts the quantitative fit tests, he makes approximately $25.00/hour, which means that by implementing D3, the USAF would save:

(49.4 hours)($25/hour) = $1,235/year

For the first year, the savings will be less than $1,235.00

because of construction costs. Materials needed to construct the mock-up cost $80.00. The worker who built the mock-up made $6.00 per hour, and the construction time was 26 hours. By adding in a $10.00 cost for other construction materials, the total cost to construct the mock-up was:

($6.00/hour)(26 hours) + $80.00 + $10.00 = <u>$246.00</u>

The final cost savings for the first year would equal:

$1,235.00 - $246.00 = <u>$989.00</u>

Assuming a three per cent per year pay raise for government employees, over the next five years the USAFSAM analyst would make the following:

Year 1 = $25.00/hour
Year 2 = $25.75/hour
Year 3 = $26.53/hour
Year 4 = $27.33/hour
Year 5 = $28.15/hour

Given the projected pay for the analyst over the next five years, the cost savings, not including maintenance costs, was computed. Assuming that all other factors remain constant, the five year cost savings realized by implementing D3 would be the sum of the numbers shown below, which is $6,313.00.

Year 1 savings = $989.00
Year 2 savings = 49.4 hours X $25.75/hour = $1,272.00
Year 3 savings = 49.4 hours X $26.53/hour = $1,311.00
Year 4 savings = 49.4 hours X $27.33/hour = $1,350.00
Year 5 savings = 49.4 hours X $28.15/hour = $1,391.00

Finally, an examination of worker output provided

interesting results. In the current work day, the analyst sets up the laboratory and tests eight subjects in 4.71 hours. By implementing the new work method and laboratory design, the analyst could test nine subjects per day and still have over seven minutes left. Through an entire year (90 testing days), this means that 110 more subjects could be tested, or the number of days needed to test 720 (90 days X 8 subjects) subjects would be reduced to 80.

6.10 USER ACCEPTANCE

The results of the questionnaire (See Appendix G) conclusively indicated that the USAFSAM analyst preferred working in the proposed laboratory rather than the current laboratory. In nine out of 10 questions, the analyst indicated that D3 was the preferred design. The main points that came from the questionnaire were that the new design was more compact, so fatigue and stress were reduced, movements to and from equipment were easier and faster, displays were easier to read so errors were reduced, and safety was enhanced due to the elimination of trip hazards. The only area in which D3 was not preferred was system maintenance. However, the analyst did say that, in the new design, the need for maintenance was reduced because accidents were infrequent.

6.11 PROBLEMS DISCOVERED WHEN USING THE MOCK-UP

Through the use of the functional mock-up, several

problems were detected. The first problem dealt with the keyboard placement. The workstation was shaped similar to the console shown in Figure 6.7. Van Cott and Kinkade [1972] suggested that a 110 degree angle be used with a wrap-around console. In D3, this was the angle used, however, when the console was assembled, and the keyboard was put in place, access to the air flow controls was obstructed. To correct the problem, a board was inserted between the base of the booth panel and the counter top upon which the computer was located. This board not only enlarged the angle discussed, but also it made access to the air flow controls simple. The larger angle was acceptable because it resulted in a more open work station.

The second problem was unexpected. The 12 inch counter top which ran along the inside of the workstation was not wide enough, thus the analyst could not conveniently place the calibration flasks on the counter top. To solve this problem, the permanent workstation should have a counter top that is, at least, 16 inches wide.

One goal of this project was to remove the VDT from atop the disk drive. This meant that the disk drive had to be located elsewhere. Optional locations included: under the counter top, on top of either panel, or on a stand similar to the one upon which the printer sits. The disk drive was originally intended to be placed on a shelf under the counter top, however, this proved impractical because

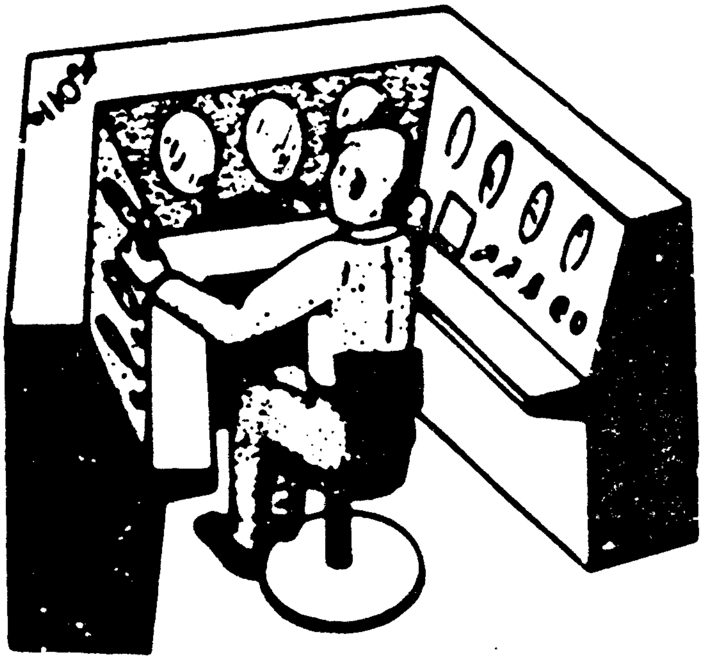


Figure 6.7 Recommended Angle for a Wrap-around Console
(Van Cott and Kinkade [1972])

while sitting, the analyst could accidentally bump the disk drive. When the other two methods were tried, the electrical cord from the disk drive would not reach the VDT. Given no other realistic alternative, the disk drive was put under the VDT. By doing this, the VDT could be plugged into the disk drive, and the horizontal line-of-sight to the booth was still maintained. This concludes the results section. In the next chapter, a brief summary of this study and recommendations are provided.

CHAPTER 7

SUMMARY AND RECOMMENDATIONS

7.1 SUMMARY

As one examines the Quantitative Fit Testing Laboratory it becomes obvious that the fit testing chamber was installed first, and other necessary equipment was added after. Because the mission of the Quantitative Fit Testing Laboratory is so important, new equipment is frequently added to the system to ensure that everything is state of the art. A problem arises when the new equipment is installed wherever there is room or wherever is convenient. Little thought is given to future maintenance considerations, ease of use, or safety problems. Thus, the computer equipment sits on a laboratory cart, copper pipes protrude into walkways, electrical wires and air hoses hang at waist level in walkways, and the balance is located four laboratories away.

The MT study brought to light some inherent problems that existed in the Quantitative Fit Testing Laboratory and in the testing procedures themselves. Through better design and laboratory layout, these problems were reduced, and in most cases, eliminated.

7.2 RECOMMENDATIONS

Due to the nature of this study, some design recommendations are provided first, followed by the

recommended areas for future study. Generally, USAFSAM should implement the procedural changes and the new layout recommended in this study. The result will be easier job performance for the analyst, and a five year cost savings of over $6,000.00 for the USAF. In addition, the USAFSAM should purchase a new chair to be used in the laboratory. Although the fit testing process lends itself to a sit-stand situation, the analyst does spend most of his day sitting at the workstation. The chair, with the recommended features, was described in Chapter 6.

Another design recommendation is to widen the 12 inch shelf which ran through the inside of the workstation. Roebuck et. al. [1975] and Van Cott and Kinkade [1972] recommended that the shelf be 16 inches. This extra four inches would be sufficient space in which to conveniently work while calibrating the instruments.

The methods analysis conducted in this study brought to light some procedural problems, these problems were corrected, and a new process was developed. The analyst was briefed on the procedures and used them for the second MT study. Continued use of this new method is recommended.

Future studies concerning the laboratory design, should examine the possibility of automating the entire testing process. Mixing solutions and making pipe connections could probably be done by robots, but that would be unnecessary. Humans are more capable of performing such activities,

however, instructing the subject to perform the next exercise, and monitoring air flows could be accomplished through automation.

Another area of study involves the system plumbing. With the exception of the computer equipment, data logger, and integrator boxes, the entire system is connected with copper pipes or rubber air hoses. This results in a maze of pipes and wires which is unpleasant to the eye, a maintenance nightmare, and results in the use of excess pipe.

Future study should also include an evaluation of the workstation instruments. Although the fit testing process itself is current, better ways to display information may be possible, particularly for the manometer hydrogen pressure gauge and the line air pressure gauge. Also, digital air flow instruments would reduce the amount of control panel space required. Updating equipment does not guarantee greater efficiency, but the possibility for improved efficiency should be examined.

In the future, more emphasis will be placed on cutting costs and increasing productivity. To meet both of these objectives, better human and machine efficiency will be necessary. Through an extensive analysis of the current quantitative fit testing process and development of a functional mock-up, a more efficient work method and laboratory design were developed and tested. The projected

improvement in worker output and cost savings were determined, and user acceptance was improved.

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APPENDIX A

Functional Flow Diagram of the
Current Setup and Testing Process

Feet Traveled		Activity
	1	Turn on Hydrogen
11	⇨	Walk to mask console
	2	Light Hydrogen and inspect
7	⇨	Walk to booth console
	3	Light Hydrogen and inspect
	4	Turn on booth power/inspect air flow
7	⇨	Walk to mask console
	5	Turn on mask power/inspect air flow
	6	Hook up pump
16	⇨	Walk to computer
	7	Sign on to computer
	D	Await computer prompt
26	⇨	Walk to sink
	8	Prepare calibration samples
66	⇨	Carry 1/2 of calibration samples to mask console, return, carry other 1/2
22	⇨	Walk to sink
	9	Prepare aerosol generator
9	⇨	Carry aerosol generator to booth
	10	Hook up aerosol generator/inspect
	11	Turn on air flow/inspect

Functional Flow Diagram of the
Current Setup and Testing Process

Feet Traveled		Activity
31		Walk to mask console
	12	Zero out instruments/inspect
		Integrator box delay
	13	Zero out booth instruments/inspect
		Integrator box delay
5		Walk to computer
	14	Call up computer program
		Computer delay
70		Carry calibration samples to sink
	15	Rinse calibration samples
29		Walk to storage closet
	16	Remove mask from closet
	17	Give mask to subject & brief
		Delay while subject dons/adjusts mask
21		Enter booth with subject
	18	Connect air tube to mask
23		Exit booth
		Check air flow
26		Walk to pump
	19	Prepare pump for operation
13		Walk to mask console
	20	Inspect/adjust air flow
11		Walk to booth console
	21	Inspect/adjust air flow

Functional Flow Diagram of the Setup and Testing Process

Feet Traveled		Activity
5	⇨	Walk to computer
	22	Plug in/test intercom
	23	Input subject/mask data
	D	Computer delay
	24	Instruct subject: heavy breathing
5	⇨	Walk to booth console
	25	Inspect/adjust air flow
11	⇨	Walk to mask console
	26	Inspect/adjust air flow
4	⇨	Walk to computer
	D	Delay (air samples being drawn)
	27	Instruct subject: side-to-side
	D	Delay (air samples being drawn)
	28	Instruct subject: up-and-down
	D	Delay (air samples being drawn)
	29	Instruct subject: read paragraph
	D	Delay (air samples being drawn)
	30	Instruct subject: Make faces
	D	Delay (air samples being drawn)
	31	Log off computer
	32	Instruct subject to exit booth
17	⇨	Walk to pump
	33	Unhook pump
17	⇨	Carry pump to sink

Functional Flow Diagram of the
Setup and Testing Process

Feet Traveled		Activity
	(34)	Flush and dry pump tuoes
17	⇨	Carry pump to mask console
6	⇨	Walk to the subject
	(35)	Receive mask from subject
11	⇨	Walk to storage
	(36)	Exchange masks

Number of operations................	○	36
Number of Delays.....................	D	11
Number of inspections...............	□	12
Number of transportations...........	⇨	26
Total number of feet traveled		486

APPENDIX B

OBSERVATION SHEET

Setup Activities	Observation Time (minutes) Present Design	Design Three
Turn on hydrogen		
Walk to mask console & light the hydrogen		
Walk to booth console & light the hydrogen		
Turn on & check air flows, turn on exhaust fan & system power		
Hook up pump		
Sign on to computer		
Prepare calibration samples		
Walk to mask console & put calibration samples in place		
Prepare aerosol generator		
Hook up aerosol generator & turn on air flow		
Make up new saline solution		
Zero out mask instruments		
Zero out booth instruments		
Call up computer program to setup regression curves for concentrations and voltages		
Rinse calibration sample flasks		

APPENDIX C

Motions Required to Setup and Test in Laboratory D1

Step	Improved Method for Laboratory Design One
1.	Turn on Hydrogen
2.	Walk to workstation, light Hydrogen, turn on DC power, check air flows & hook up pump (mask)
3.	Walk to workstation, light Hydrogen, turn on DC power, check air flows & hook up pump (booth)
4.	Walk to & sign on the computer
5.	Walk, turn on exhaust fan & system power, check air flows
6.	Walk to sink & prepare calibration samples, load samples into carrier & prepare aerosol generator
7.	Walk to booth, hook up aerosol generator & check air flow
8.	Walk to sink & make new saline solution
9.	Walk to chair, turn to atomizer holder, unhook pump, zero out instruments & load samples into carrier
10.	Carrying the calibration samples, slide to booth panel, unhook pump & zero out instruments
11.	Slide to the computer & call up regression program
12.	Walk to sink & rinse calibration sample flasks
13.	Brief subject on test procedures, walk to storage, remove mask & give mask to subject
14.	Subject adjusts & dons mask
15.	Enter booth & connect sample drying air tube to mask
16.	Exit booth & adjust sample air flow behind booth

Motions Required to Setup and Test in Laboratory D1

Step	Improved Method for Laboratory Design One
17.	Walk to workstation, sit & prepare pump for operation
18.	Turn to adjust sample air flows for the mask
19.	Turn to booth panel & adjust sample air flow
20.	Turn & instruct subject to breath normally
21.	Input subject & mask data & instructions to data logger
22.	Await computer prompt/instruct subject to begin heavy breathing
23.	Turn & check air flows to mask
24.	Turn & check air flows to booth & turn back to the computer
25.	Await computer prompt/instruct subject to move head from side-to-side
26.	Await computer prompt/instruct subject to move head up and down
27.	Await computer prompt/instruct subject to read paragraph
28.	Await computer prompt/instruct subject to make faces
29.	Await computer prompt/instruct subject to unhook the sample air line & exit, log-off the computer
30.	Stand, unhook mask pump, and carry pump to the sink
31.	Flush & dry air tubes for pump
32.	Return pump to workstation
33.	Walk to storage & exchange masks with subject

APPENDIX D

Motions Required to Setup and Test in Laboratory D2

Step	Improved Method for Laboratory Design Two
1.	Turn on Hydrogen
2.	Walk to workstation, light Hydrogen, turn on DC power, check air flows & hook up pump (mask)
3.	Walk to workstation, light Hydrogen, turn on DC power, check air flows & hook up pump (booth)
4.	Walk to & sign on the computer
5.	Walk, turn on exhaust fan, system power & check air flows
6.	Walk to sink & prepare calibration samples, load samples into carrier & prepare aerosol generator
7.	Walk to booth, hook up aerosol generator & check air flow
8.	Walk to sink & make new saline solution
9.	Walk to chair, slide to atomizer holder, unhook pump & zero out mask instruments
10.	Unhook pump & zero out booth instruments
11.	Slide to the computer & call up regression program
12.	Walk to sink & rinse calibration sample flasks
13.	Brief subject on test procedures, walk to storage, remove mask & give mask to subject
14.	Subject adjusts & dons mask
15.	Enter booth & connect sample drying air tube to mask
16.	Exit booth & adjust sample air behind booth
17.	Walk to workstation, sit & prepare pump for operation

Motions Required to Setup and Test in Laboratory D2

Step	Improved Method for Laboratory Design Two
18.	In chair, slide to adjust sample air flow for the booth
19.	Slide to the mask instruments and adjust sample air flow
20.	Slide to computer & instruct subject to breath normally
21.	Input subject & mask data & instructions to data logger
22.	Await computer prompt/instruct subject to begin heavy breathing
23.	Slide in the chair to check the air flows to the mask
24.	Slide in the chair to check air flows to the booth & slide back to the computer
25.	Await computer prompt/instruct subject to move head from side-to-side
26.	Await computer prompt/instruct subject to move head up and down
27.	Await computer prompt/instruct subject to read paragraph
28.	Await computer prompt/instruct subject to make faces
29.	Await computer prompt/instruct subject to unhook the sample air line & exit the booth, log-off the computer
30.	Stand, unhook mask pump & carry pump to the sink
31.	Flush & dry air tubes for the pump
32.	Return pump to the workstation
33.	Walk to storage & exchange masks with subject

APPENDIX E

Motions Required to Setup and Test in Laboratory D3

Step	Improved Method for Laboratory Design Three
1.	Turn on Hydrogen
2.	Walk to workstation, light Hydrogen, turn on DC power, check air flows & hook up pump (mask)
3.	Walk to workstation, light Hydrogen, turn on DC power, check air flows & hook up pump (booth)
4.	Walk to & sign on computer
5.	Walk to & turn on exhaust fan & system power & check air flows
6.	Walk to sink, prepare calibration samples, load samples into carrier & prepare aerosol generator
7.	Walk to booth, hook up aerosol generator & check air flow
8.	Walk to sink & make new saline solution
9.	Walk to chair, turn to atomizer holder, unhook pump, zero out mask instruments and load samples into carrier
10.	Turn chair to booth panel & zero out booth instruments
11.	Turn to the computer & call up regression program
12.	Walk to sink ? rinse calibration sample flasks
13.	Brief subject on test procedures, walk to storage, remove mask & give mask to subject
14.	Subject adjusts & dons mask
15.	Enter booth & connect sample drying air tube to mask
16.	Exit booth & adjust sample air behind booth
17.	Walk to workstation, sit & prepare pump for operation

Motions Required to Setup and Test in Laboratory D3

Step	Improved Method for Laboratory Design Three
18.	Adjust sample air flow for the booth
19.	Adjust sample air flow for mask
20.	Instruct the subject to breath normally
21.	Input subject & mask data & instructions to data logger
22.	Await computer prompt/instruct subject to begin heavy breathing
23.	Check the air flows to the mask
24.	Check air flows to the booth
25.	Await computer prompt/instruct subject to move head from side-to-side
26.	Await computer prompt/instruct subject to move head up & down
27.	Await computer prompt/instruct subject to read paragraph
28.	Await computer prompt/instruct subject to make faces
29.	Await computer prompt/instruct subject to unhook the sample air tube & exit the booth, log-off the computer
30.	Turn to unhook mask pump & carry pump to the sink
31.	Flush & dry air tubes for the pump
32.	Return pump to workstation
33.	Walk to storage & exchange masks with subject

APPENDIX F

OBSERVATION SHEET

Setup Activities	Observation Time (minutes) Current Design	Design Three
Turn on Hydrogen	.06	.06
Walk to mask console & light the Hydrogen	.46	.48
Walk to booth console & light the Hydrogen	.18	.24
Turn on & check air flows, turn on exhaust fan and system power	.83	.50
Hook up pump	1.00	*
Walk to and sign on to computer	.33	.19
Walk to sink and prepare calibration samples	5.04	6.22
Walk to mask console and put calibration samples in place	.48	*
Walk to sink and prepare aerosol generator	2.22	1.67
Walk to booth, hook up aerosol generator and turn on air flow	.37	.63
Walk to sink and make up new saline solution	20.11	19.39
Walk to mask console and zero out instruments	13.19	10.60
Walk to computer & call up program to setup regression curves for concentrations and voltages	1.12	1.55
Walk to sink and rinse calibration sample flasks	3.58	3.44

OBSERVATION SHEET

Testing Activities	Observation Time (minutes) Current Design	Design Three
Brief subject on test procedures, walk to storage closet, remove mask and give mask to subject	.21	.20
Subject adjusts and dons mask	.92	.92
Enter booth and connect sample drawing air tube to mask	.38	.33
Exit booth and check air flow	.52	.52
Walk to sample line, plug line into pump and plug in pump	.39	.36
Walk to mask console and adjust sample air flow	.17	.07
Walk to booth console and adjust sample air flow	.07	.06
Walk to chair, plug in and test intercom by instructing subject to breath normally	.20	.001
Place keyboard on lap, input subject and mask data, as well as instructions to data logger	.43	.36
Await computer prompt and instruct subject to begin heavy breathing	.78	.78
Carry intercom, walk to booth console and check air flow	.13	.07
Return intercom, walk to mask console, check air flow, return to computer	.15	.09
Await computer prompt & instruct subject to move head from side to side	.77	.77
Await computer prompt & instruct subject to move head up and down	.77	.77

OBSERVATION SHEET

Testing Activities	Observation Time (minutes) Current Design	Design Three
Await computer prompt & instruct subject to read the paragraph	.80	.80
Await computer prompt & instruct subject to make faces	.81	.81
Await computer prompt & instruct subject to unhook the tube & exit, log-off computer & place keyboard atop the computer	.74	.67
Walk to pump, remove tube, unplug pump & carry to sink	.52	.17
Flush and dry air tube	.46	.46
Return pump to mask console	.22 *	.08
Receive mask from subject, wall storage & retrieve next mask to be tested	.30	.28
Total setup time	48.97	44.20
Total testing time	9.74	8.57
Total time	58.71	52.77

NOTE: The procedures used in design three were developed in this project, therefore, what appears to be an unreasonable difference between the current design and D3 times may actually be the result of a procedural change.

* these steps were combined with other steps in design three as part of the recommended improvements in this project

APPENDIX B

QUESTIONNAIRE

1. In which design is system maintenance easier to perform?

A. CURRENT DESIGN B. MOCK-UP DESIGN C. **SAME**

What characteristics of this system make maintenance easier to perform?

Response: System maintenance will not be easier to perform in either design, but with the new design, the need for maintenance will probably be lower for a couple reasons. First, in the old design, the keyboard was accidentally dropped while I was putting it on my lap; now there is a permanent place for the keyboard. Second, with the old design, the intercom fell several times because it was hanging off the edge of the laboratory cart. Wires have been removed from the walkways so trip hazards are gone, and accidentally pulling equipment onto the floor (by tripping on the cord) is no longer a problem.

2. Which design provides a safer work environment?

A. CURRENT DESIGN B. **MOCK-UP DESIGN** C. SAME

What characteristics of this design make it safer?

Response: The new design provides a safer work environment because trip hazards were eliminated.

3. In which design are fewer errors made during setup and testing?

A. CURRENT DESIGN B. **MOCK-UP DESIGN** C. SAME

To what do you attribute this reduction in errors?

Response: Because the air lines are shorter, less aerosol is trapped (lost) in the lines. Trapped aerosol throws off the sample calibration.

QUESTIONNAIRE

4. In which design are the instrument labels easier to read?

A. CURRENT DESIGN B. **MOCK-UP DESIGN** C. SAME

Do these labels more effectively discriminate among equipment pieces than the labels used in the other design? **YES** NO

Response: This is primarily true for the integrator boxes. In the present design, the integrator boxes were occasionally confused. With the new design, this confusion was eliminated. Also, with the new design, the instruments themselves are easier to read.

5. Which design provides unhindered access to and from the work area and between equipment?

A. CURRENT DESIGN B. **MOCK-UP DESIGN** C. SAME

What characteristics of the design make this possible?

Response: Having the equipment closer to the computer and having the laboratory less cluttered are two characteristics that make it easier to travel in the laboratory. Also, the trip hazards were eliminated.

6. Which design provides shorter and clearer visual links between equipment?

A. CURRENT DESIGN B. **MOCK-UP DESIGN** C. SAME

COMMENTS: None

7. Which design provides greater ease of use of instruments?

A. CURRENT DESIGN B. **MOCK-UP DESIGN** C. SAME

What characteristics of this design make the instruments easier to use?

Response: The equipment is closer together and most of the work can be accomplished while sitting. Also, the equipment is easier to see because the viewing distances were shortened. The carry box made transporting the calibration samples very simple.

QUESTIONNAIRE

8. Which design allows for greater speed of movements between equipment?

A. CURRENT DESIGN B. **MOCK-UP DESIGN** C. SAME

What design characteristics make speedier movements possible?

Response: Because the instruments are easier to see, it takes less time to identify the information which is displayed. Speedier movements were possible because the equipment was closer together.

9. Which design do you feel reduces psychological and physiological stresses the most?

A. CURRENT DESIGN B. **MOCK-UP DESIGN** C. SAME

To what do you attribute the reduction of stress?

Response: Psychological stress was reduced because I did not have to worry about whether I had read the instrument display correctly or not, or whether I had even checked the instrument at all. With everything so spread out in the present laboratory, it is difficult to keep track of which instruments have been checked. The potential for claustrophobia exists because the console has a wrap-around shape, but so far, claustrophobia is not a problem.

Physiological stress was reduced because movement is reduced. Less standing up and sitting down is required and walking is reduced.

10. Which design do you feel reduces physical fatigue the most?

A. CURRENT DESIGN B. **MOCK-UP DESIGN** C. SAME

To what do you attribute the reduction of fatigue?

Response: Less movement was required, more sitting was possible, there was a shelf to rest my arms on, and I did not have to move the keyboard and intercom every time I stood up.